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Report No. A-10

FINAL REPORT (NASW-2144)

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by

Astro Sciences

of

IIT Research Institute
Chicago, Illinois

for

Lunar and Planetary Programs

Office of Space Science and Applications

NASA Headquarters

Washington, D. C.

APPROVED

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Physics Research Division

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FOREWORD

This final report summarizes the reports prepared and the special tasks performed by Astro Sciences of IIT Research Institute during the twelve month period from November 1970, through October 1971. Eight reports and technical memoranda are summarized together with a description of seventeen advanced planning tasks on which no formal reports have been written. A summary of the Astro Sciences coordinated Yerkes Cometary Science Symposium is also contained within this report along with the abstracts of four technical papers which have been published in the open literature. This work has been performed under NASA Contract Number NASW-2144.

EIGHTH ANNUAL SUMMARY REPORT

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FINAL REPORT (NASW-2144)

LONG RANGE PLANNING FOR SOLAR SYSTEM EXPLORATION

NOVEMBER, 1970 - OCTOBER, 1971

1. INTRODUCTION

Astro Sciences of IIT Research Institute (AS/IITRI) has been engaged in a program of advanced research, study and analysis for the Planetary Programs Division (Code SL) of NASA since March, 1963. The results of Astro Sciences' work up to October 31, 1970, have been previously reported[1]. This report summarizes the work performed on Contract NASW-2144 from November 1, 1970 through October 31, 1971.

The purpose of advanced mission planning is to derive a preliminary understanding of those missions, and associated mission requirements, which are of importance in the evolution of knowledge of our solar system. It is necessary not only to have a solid foundation in science and engineering for this type of planning but also the ability to integrate the increasing awareness of the problems involved in space exploration back into the advanced planning process. Astro Sciences' program during the period covered by this report, as it has during the previous seven years, has continued to develop this process in accordance with NASA's broadening needs.

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1 The contract work conducted between March 1, 1963 and December 1, 1968 is summarized in AS/IITRI Report No. A-6, "Long Range Planning Studies for Solar System Exploration" (1969). Work done between December 1, 1968 and October 31, 1969 is summarized in AS/IITRI Report No. A-7, "Long Range Planning for Solar System Exploration" (1970). Work done between November 1969 and October 1971 is summarized in AS/IITRI Report No. A-9, "FINAL REPORT" (NASW-2023) (1970).

The continuing activities of Astro Sciences are reported to the Planetary Programs Division at regularly scheduled bi-monthly review meetings. However, the most tangible output is in the form of technical reports and memoranda. During the twelve months covered by this report a total of eight reports or technical memoranda have been submitted. Summaries of these documents are given in Section 2. Section 3, Special Studies, Activities and Technical Notes, contains a summary of the Proceedings of the Cometary Science Working Group sponsored by NASA and organized by Astro Sciences. This section also summarizes study efforts that have been performed and capabilities that exist but for which no formal reports have been published. Section 4 contains abstracts of those papers published and presented by Astro Sciences staff members which originated primarily as a result of work performed under this contract. Section 5 contains a bibliography of reports and technical memoranda published by AS/IITRI. Finally Section 6 summarizes the major computer programs used to support Astro Sciences' technical efforts.

2. SUMMARY OF REPORTS AND TECHNICAL MEMORANDA PUBLISHED NOVEMBER 1970 - OCTOBER 1971

2.1 MISSION OBJECTIVES

Technical Memorandum No. P-39
"SCIENCE PAYLOAD FOR FIRST JUPITER ORBITERS"
Astro Sciences, J. C. Niehoff (ed.)
February, 1971 (9 pp., 6 refs.)

A total of 16 instruments were identified (Table 1) which are candidates for a first Jupiter orbiter mission. Of these, 11 are considered essential. Five of the 11 are related to planet and satellite measurables (planetology), four are included for investigation of the surrounding environment (fields/particles) and the remaining two, radio occultation and precision tracking, can be classified as earth/spacecraft experiments not requiring specific science payload instruments. Although, by definition, this is a preliminary payload, it is felt that the included instruments reflect the capability to investigate the most important orbiter objectives which can be identified at this time.

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TABLE I

SUMMARY OF CANDIDATE EXPERIMENTS FOR SINGLE JUPITER ORBITER MISSIONS

GENERIC INSTRUMENT DESCRIPTION	MEASURABLES * / DEFINITION	EXPLORATION REGIMES: ATMOSPHERE							SURFACE & INTERIOR				FIELDS & PARTICLES				
		COMPOSITION (J)	IONOSPHERE & EXOSPHERE (J)	GLOBAL CIRCULATION (J)	LOCAL PHENOMENA (J)	CLOUD STRUCTURE (J)	THERMODYNAMICS (J)	ATMOSPHERE IDENTIFICATION (S)	ENERGY BALANCE (J/S)	STATIC & DYNAMIC SHAPE (J/S)	ROTATION VECTOR (J/S)	SURFACE APPEARANCE & COMP. (S)	ELECTROMAGNETIC & GRAVITY FIELDS (J/S)	TRAPPED CHARGED PARTICLES (P)	DUST PARTICLES (P)	SOLAR WIND INTERACTION (P)	EXOBIOLOGY (J)
	NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ESSENTIAL INSTRUMENT PACKAGE:																	
TV (MEDIUM-ANGLE FOV)				X	X	X				X	X	X			X		
PHOTOMETER/POLARIMETER **		X				X		X				X			X		
UV SPECTROPHOTOMETER		X	X				X	X									X
IR RADIOMETER						X	X		X			X					
RADIO EMISSION RECEIVER											X		X	X			
MAGNETOMETER											X		X			X	
PLASMA DETECTORS/ANALYZERS																X	
CHARGED PARTICLE DETECTORS														X			
MICROMETEORITE DETECTORS															X		
RADIO OCCULTATION		X	X				X			X							
PRECISION TRACKING										X			X				
ADDITIONAL DESIRABLE INSTRUMENTS:																	
TV (NARROW-ANGLE FOV)					X	X						X					
IR LINE-SCANNER				X	X	X						X					
IR SPECTROMETER		X					X	X				X					X
MICROWAVE RADIOMETER							X		X								
X-RAY DETECTOR			X											X			

*(J)-APPLIES TO JUPITER, (S)-APPLIES TO JOVIAN SATELLITES, (J/S)-APPLIES TO JUPITER & SATELLITES
(P)-APPLIES TO PLANETARY SYSTEM

** THE FUNCTION OF THIS INSTRUMENT IS REGARDED ESSENTIAL, THE INSTRUMENT ITSELF IS NOT. ITS CHARACTERISTICS MAY BE INCORPORATED WITH THE TV SYSTEM.

2.2 MISSION ANALYSIS

Report No. M-26
"MERCURY ORBITER MISSION STUDY"
By D. A. Klopp
June, 1971 (167 pp, 56 refs.)

This report provides a preliminary analysis of an unmanned Mercury orbiter mission which might be flown in the early 1980's. In addition to investigating the applicability of solar electric low-thrust technology to such a mission, the study also identifies scientific objectives for a Mercury orbiter, provides estimates of science payloads appropriate to a Mercury orbiter, and compares several mission concepts for an early orbiter mission.

Approximately 35 specific "measurables" are identified as relevant to the scientific exploration of Mercury. These measurables are listed in Figure 1. Three groupings are shown in the figure: (1) those measurables likely to be investigated by an orbiter mission, (2) those likely to be investigated by a combination of orbiter and lander missions, and (3) those likely to be investigated by lander missions alone. The figure also provides an evaluation of the utility of various measurement techniques in studying these measurables. The major role expected of an orbiter is that of obtaining global surface imagery of one to three km resolution, which is not likely to be provided by flyby missions. Visual imagery experiments performed from an orbiter would be most useful in investigating surface elevations, lithologic contacts, surface topography, surface appearance, and the orientation of Mercury's rotation axis. Lander and orbiting spacecraft working together would prove most valuable for objectives requiring both extensive surface mapping and ground truth measurements, such as the

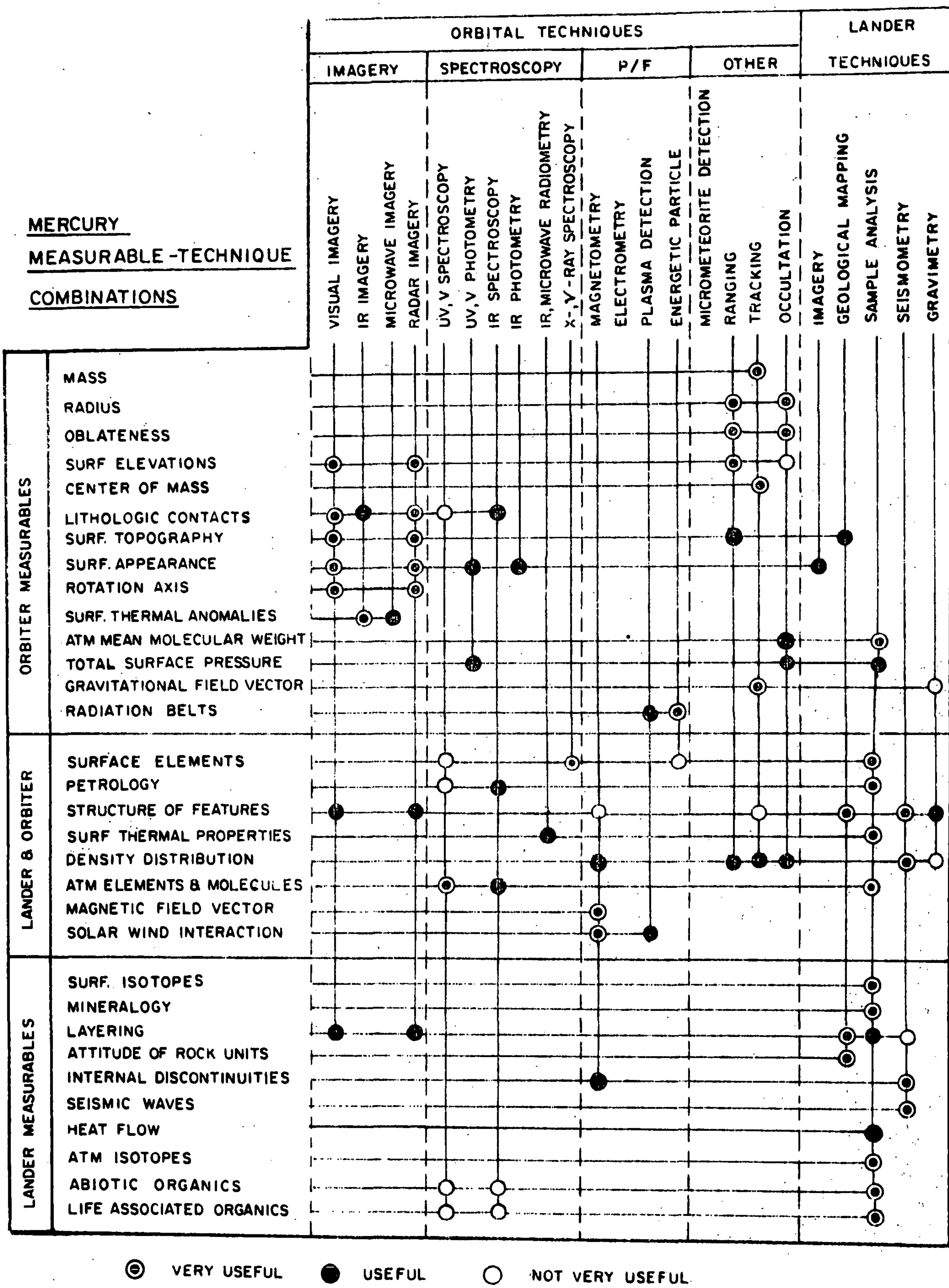
MERCURY
MEASURABLE-TECHNIQUE
COMBINATIONS
ORBITAL TECHNIQUES
LANDER TECHNIQUES
IMAGERY
SPECTROSCOPY
P/F
OTHER
VISUAL IMAGERY
IR IMAGERY
MICROWAVE IMAGERY
RADAR IMAGERY
UV, V SPECTROSCOPY
UV, V PHOTOMETRY
IR SPECTROSCOPY
IR PHOTOMETRY
IR, MICROWAVE RADIOMETRY
X-, γ-RAY SPECTROSCOPY
MAGNETOMETRY
ELECTROMETRY
PLASMA DETECTION
ENERGETIC PARTICLE
MICROMETEORITE DETECTION
RANGING
TRACKING
OCCULTATION
IMAGERY
GEOLOGICAL MAPPING
SAMPLE ANALYSIS
SEISMOMETRY
GRAVIMETRY
ORBITER MEASURABLES
MASS
RADIUS
OBLATENESS
SURF ELEVATIONS
CENTER OF MASS
LITHOLOGIC CONTACTS
SURF. TOPOGRAPHY
SURF. APPEARANCE
ROTATION AXIS
SURF. THERMAL ANOMALIES
ATM MEAN MOLECULAR WEIGHT
TOTAL SURFACE PRESSURE
GRAVITATIONAL FIELD VECTOR
RADIATION BELTS
LANDER & ORBITER
SURFACE ELEMENTS
PETROLOGY
STRUCTURE OF FEATURES
SURF THERMAL PROPERTIES
DENSITY DISTRIBUTION
ATM ELEMENTS & MOLECULES
MAGNETIC FIELD VECTOR
SOLAR WIND INTERACTION
LANDER MEASURABLES
SURF. ISOTOPES
MINERALOGY
LAYERING
ATTITUDE OF ROCK UNITS
INTERNAL DISCONTINUITIES
SEISMIC WAVES
HEAT FLOW
ATM ISOTOPES
ABIOTIC ORGANICS
LIFE ASSOCIATED ORGANICS
VERY USEFUL
USEFUL
NOT VERY USEFUL

FIGURE 1.

study of surface elemental composition and petrology, the structure of observed surface features, and the structure of the interior. The determination of surface isotopic abundances and surface minerology and the detection and study of pre-biotic phases of extraterrestrial life require lander missions, but not orbiters.

Specific measurements have been defined (in terms of desired resolution, planetary coverage, lighting conditions, etc.) for those measurables which can be investigated from an orbiting spacecraft. These measurement definitions then form the basis for estimating the weight, power, and data rate requirements of the scientific instrumentation of various orbiter missions. Five mission classes, shown in Figure 2, have been identified:

A. A "particles and fields" spacecraft of nearly 200 kg, carrying 22 kg of particles and fields instrumentation along with a few low data-rate non-imaging planetology instruments in a moderately eccentric orbit of medium inclination.

B. A "minimum planetology" spacecraft of about 250 kg carrying 27 kg of science instruments including a television camera and an infra-red spectrometer. The emphasis is upon regional scale (3 km resolution) surface examination conducted from a low-altitude circular polar orbit.

MISSON	SPACECRAFT MODEL(S)		SCIENCE	ORBITER	PERIAPSE ALTITUDE	ϵ	INCLINATION	ORBIT PERIOD
A	PARTICLES AND FIELDS		22 kg	198 kg	500 km	0.6	50°	7.4^h
B	MINIMUM PLANETOLOGY		27	267	500	0	90	1.9
C	BASELINE PLANETOLOGY		67	437	500	0	90	1.9
D	BROAD FIRST LOOK	(A)	22	198	500	0.6	50	7.4
		(C)	67	437	500	0	90	1.9
E	MAXIMUM PLANETOLOGY	(B)	44	303	2000	0	0	3.4
		(C)	67	437	500	0	90	1.9

FIGURE 2. CANDIDATE ORBITER MISSION SET

C. A "baseline planetology" spacecraft of somewhat more than 400 kg carrying nearly 70 kg of science instruments. Here the emphasis is upon regional and local (150 meters resolution) scale imagery, although the payload also includes three spectrometers, a radiometer, and an altimeter. A low-altitude circular polar orbit is used as with the smaller planetology spacecraft.

D. A "broad first look" dual satellite concept consisting of the baseline planetology orbiter and the particles and fields orbiter.

E. A "maximum planetology" dual satellite concept consisting of the baseline planetology satellite and the minimum planetology satellite in a circular equatorial orbit of higher altitude to provide repetitive coverage of equatorial and mid-latitude surface areas.

The capabilities and characteristics of these orbiter concepts are described in the report.

The case for a ballistic Mercury orbiter is shown in Figure 3, which portrays orbiting spacecraft mass as a function of orbit eccentricity with launch vehicle class as a parameter. A Titan IIID(7)/Centaur class vehicle is required to perform the particles and fields mission, an Intermediate-20 to perform the minimum planetology mission, and an Intermediate-20/Centaur to perform the minimum planetology mission, and an Intermediate-20/Centaur to perform the baseline planetology mission. The dual satellite missions both require the Intermediate-20/Centaur.

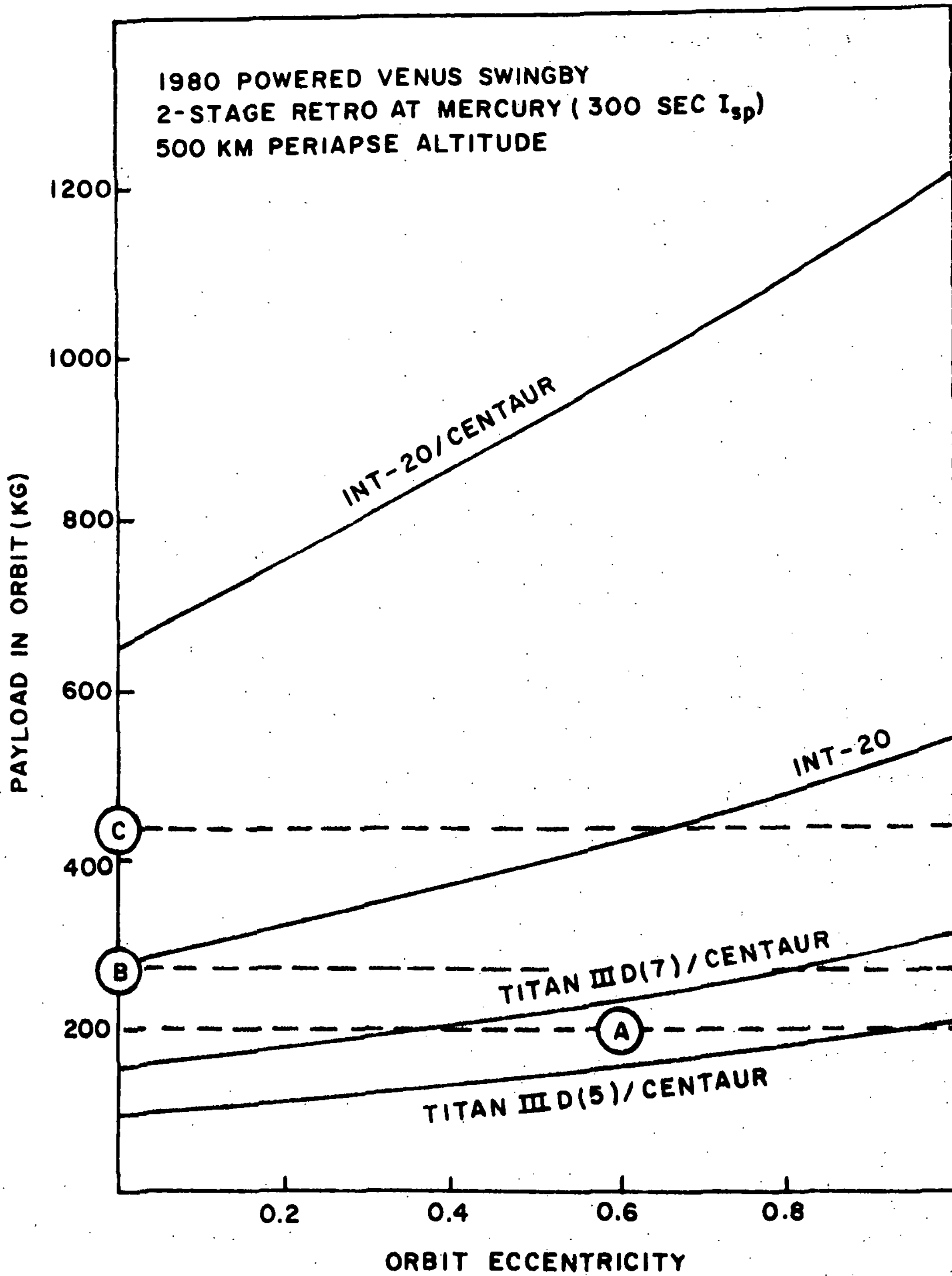

FIGURE 3. BALLISTIC MODE DELIVERY CAPABILITIES

The results shown apply only to a ballistic launch in November 1980 with a gravity-assist maneuver performed at Venus on the way to Mercury. The swingby maneuver involves an impulsive ΔV of about 0.9 km/ sec to prevent the spacecraft from entering the atmosphere of Venus. The flight time for this mission is 124 days. Many other ballistic opportunities are discussed in the report, but this particular opportunity presents very nearly the best available case (for 1980 through 1993) for the ballistic mission mode. Actually, the 1988 powered Venus swingby opportunity is a slightly better opportunity in the sense that the particles and fields orbiter can be delivered with a Titan IIID(5)/Centaur. No changes occur in the launch vehicle requirements for the other mission classes. The 1988 opportunity, however, involves a 300 day flight time.

The case for the solar electric low-thrust flight mode is shown in Figure 4, which gives payload mass in orbit as a function of interplanetary flight time based on a 500 km altitude circular orbit at Mercury and a Titan IIID(5)/Centaur class launch vehicle. The solar electric stage is assumed to have a specific mass of 30 kg per kw and the thrust is assumed variable in jet power and direction but operates at a constant specific impulse. The upper curve in the figure applies to a solar electric state of optimum power level and specific impulse, while the lower curve applies to a 15 kw solar electric stage with a specific impulse of 2500 sec. The optimum specific impulse for the 15 kw stage is less than 2500 sec, but 2500 sec is regarded as the lowest feasible value for the specific impulse. In both cases, the orbital payload which can be delivered increases with increasing flight time. However, if the power level is restricted to 15 kw a flight time of 370 days or longer is required for the baseline planetology mission. (Mission "C" is represented by the horizontal dashed line at 437 kg). Only a 300 day flight time is required for the minimum

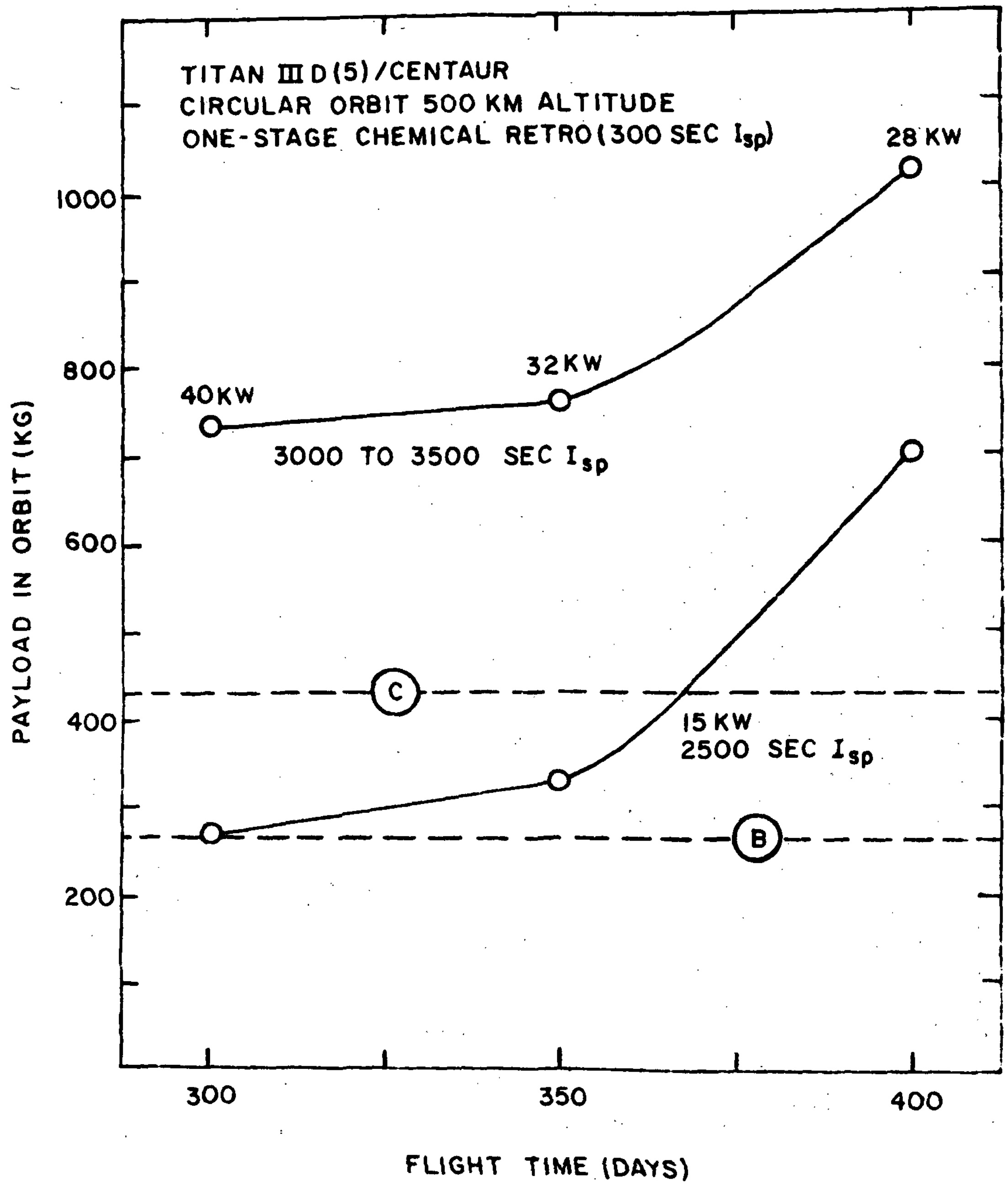

FIGURE 4. SOLAR ELECTRIC MODE DELIVERY CAPABILITIES (TITAN IIID (5)/CENTAUR)

planetology mission. The dual satellite mission could be flown with the 15 kw solar electric stage, but would require flight times in excess of 400 days. The results shown are based on using 1982 launch opportunities, and are presumed to be representative of what can be achieved by using the solar electric low-thrust mode.

Both the ballistic mode and solar electric mode results presented here are based on an impulsive orbit capture maneuver at Mercury using a chemical system of 300 sec specific impulse. For the low approach velocities of the solar electric mode, a single stage retro is adequate, while for the higher approach velocities of the ballistic mode, a two-stage retro has been assumed. That is, in the solar electric mode, the interplanetary low-thrust stage is jettisoned prior to the orbit capture maneuver. Estimates have been made of the effects of retaining the low-thrust stage and performing a low-thrust spiral capture rather than utilizing a chemical retro system. The spiral capture maneuver increases both the orbital payload and the total flight time, relative to the impulsive capture maneuver. For a total flight time of 350 days, the injected payload increases from 760 to 950 kg for the solar electric mission, but this increase drops off to only 50 kg at 400 days flight time. These payload increases are not felt to compensate for the increased complexity (in particular with regard to solar panel orientation during the spiral capture) of performing a low-thrust capture maneuver. This conclusion appears to be sensitive to the altitude of the desired final orbit. If a high-altitude orbit at Mercury were acceptable, the low-thrust capture might offer more advantage than suggested here.

The results summarized here indicate that even for the most favorable launch opportunities, an Intermediate-20 class launch vehicle is required to deliver a minimal surface-imaging

science package into Mercury orbit using a ballistic mission mode with multiple chemical propulsion stages. Employment of a 15 kw solar electric low-thrust interplanetary stage permits delivery of a larger, more capable surface-imaging science package with a Titan IIID(5)/Centaur or even a Titan IIIC/Centaur (at over 400 day flight time).

CONTENTS

Technical Memorandum No. M-27

"PRELIMINARY ANALYSIS OF URANUS/NEPTUNE ENTRY PROBES FOR GRAND TOUR MISSIONS"

AN INTERIM REPORT

BY M. J. Price and J. I. Waters

July, 1971 (44 pp, 12 refs.)

This report presents interim results of a study which will provide a preliminary definition of atmospheric entry probe configurations for deployment into the atmospheres of Uranus and Neptune. The study is based upon current estimates of the atmospheric properties of the two planets and the science payload was configured to measure these properties to 100 atmospheres. The probes are designed to be carried aboard Grand Tour spacecraft on the 1979 Jupiter-Uranus-Neptune and 1981 Saturn-Uranus-Neptune mission opportunities.

It is expected that atmospheric entry can be accomplished at either planet with flight path angles of up to -40 degrees with an ablative mass loss of less than ten percent of entry weight and a peak acceleration of less than 800 Earth g's. Probe diameters are less than 1 meter and the on-board weight will be less than 141 kilograms per probe. A spacecraft with two probes will require a Titan IIID(7)/Centaur/BII booster to accomplish the JUN-79 mission.

It was found that simple probe configurations will require over two hours to reach 100 atmospheres. This long descent time along with the low spacecraft altitude and cross track probe motion associated with the JUN-79 Uranus mission

results in an over the horizon entry point which makes continuous probe to spacecraft communication impossible. Examination of this problem and a redesign of the probe and mission configurations to accommodate it will be completed during the remainder of the study.

CONTENTS

SECTION

Report No. M-28
"COMET RENDEZVOUS MISSION STUDY"
By A. L. Friedlander and W. C. Wells
October, 1971 (132 pp, 30 refs.)

The primary objective of this report is to establish the value and characteristics of comet rendezvous missions. Rendezvous, compared with flythrough, has the advantage of a much longer observation time and the opportunity to do extensive spatial exploration. Four periodic comets with perihelia between 1980 and 1986, Encke, d'Arrest, Kopff and Halley, were recommended in a previous study as good candidate missions (Friedlander et. al., 1970). Comet P/Halley is well known because it is easily seen once each 76 years with the unaided eye. Since it has the shortest period and smallest perihelion distance, astronomers have studied P/Encke more extensively than the other periodic comets. The other two are typical short-period comets. These comet apparitions are especially favorable for rendezvous missions because of early Earth-based comet recovery, good opportunities to view the activity from Earth and reasonable launch vehicle and trajectory requirements for nominal payloads.

Nine significant scientific questions are listed in abbreviated form in the left-hand column of Figure 5. These questions are concerned primarily with composition, processes modifying composition and the loss of material from the comet. Answers are required to understand the origin of comets and the dynamics of cometary phenomena. For each question the useful science instruments are indicated with an "X". Simultaneous observations of the comet from the spacecraft and the Earth will be complimentary, but more importantly will improve the past and

FIGURE 5 INSTRUMENT USE FOR COMET RENDEZVOUS MISSIONS

QUESTIONS / INSTRUMENTS	SCIENCE TV	UV, V SPECTROMETER	PHOTOMETER/RADIOMETER	MASS SPECTROMETER	SOLID PARTICLE DETECTOR	PLASMA ANALYZER	MAGNETOMETER	PLASMA WAVE DETECTOR	RADIO TRACKING
WHAT IS THE COMET NUCLEUS LIKE?	X		X						
WHAT HAPPENS TO THE NUCLEUS AT PERIHELION?	X		X	X	X				
WHAT HAPPENS TO THE NUCLEUS AT APHELION?	X		X						
WHAT IS THE COMPOSITION OF THE PARENT MOLECULES?				X					
WHAT IS THE COMPOSITION OF THE DUST PARTICLES?					X				
WHAT NON-GRAVITATIONAL FORCES ACT ON THE NUCLEUS?									X
HOW ARE MOLECULES AND IONS FORMED?		X		X		X			
HOW ARE MOLECULES AND IONS DISTRIBUTED IN SPACE?		X		X		X			
HOW DOES THE COMET INTERACT WITH THE SOLAR WIND?						X	X	X	
HOW LARGE ARE THE SOLID PARTICLES?			X		X				
WHAT CAUSES SUDDEN CHANGES IN COMET ACTIVITY?		X		X		X	X	X	

future interpretations of spatial, spectral and temporal observations of other comets. Equally important is the coordination of in-situ and remote sensing measurements which will allow the conditions at other locations to be related to those near the spacecraft. An arrival date of 50 days before perihelion and a mission duration of about 100 days are required to take full advantage of opportunities to study comet activity.

Following rendezvous a stationkeeping program is initiated to do the spatial investigation. Circumnavigations of the nucleus at a distance of about 100 km will allow close-up examination of the center of activity and source of material. Radial traverses to about 20,000 km will study changes in composition, the effects of the solar wind interaction and the sources of both the plasma and dust tails. In-situ exploration of the nucleus is best accomplished using a deployed probe. Since there is little interference with the program to explore the coma and no additional hazard to the spacecraft, this concept provides high quality scientific data for a modest increase in spacecraft complexity. The weight of the probe is taken as 60 kg.

A nominal science instrument package has been assembled using currently available or proposed devices. In addition to those instruments listed across the top of Figure 5, the package includes an approach acquisition TV. The science TV images the nucleus during the circumnavigations. The mass spectrometer and a UV, V spectrometer are a complimentary combination of an in-situ instrument and a remote sensor, since both measure molecular and ion abundances. Similarly the photometer/radiometer and the solid particle detector both measure the dust in the coma. New instrument developments are needed to determine the composition of more energetic ions and of solid particles. The magnetometer, plasma analyzer and plasma wave detector are included to observe the interaction between the comet and the solar wind and magnetic field.

Allowing 10 percent for the desired improvements, the total weight, power consumption and data rate for the nominal science instruments are 70 kg, 90 watts and 3.6×10^8 bits per day, respectively.

The weights of spacecraft subsystems given in Table 2 were estimated using scaling laws. Briefly the requirements are 70 kg of science instruments, a 40 kbps data rate capability at 2.0 AU, storage of one day's data, a total power of 250 watts at 2.0 AU and 200 m/sec for midcourse and stationkeeping maneuvers. The subsystem differences between a ballistic spacecraft and an integrated SEP design are small. The latter obtains power and maneuvering capability from the SEP systems. However, increases were made in the computer/sequencer and attitude control subsystems to account for the additional complexity and larger moment of inertia of an SEP design. The comet environment requires the addition of meteoroid protection but the amount needed is uncertain. In addition a technique other than star sensing must provide the attitude reference when the spacecraft is near the comet nucleus. Jettisoning the SEP system at rendezvous offers no advantages over the integrated design, and would, in fact, require a larger net payload.

Rendezvous missions to the short-period comets Encke, d'Arrest and Kopff can be accomplished with solar electric propulsion or ballistic (chemical propulsion) systems launched by Titan/Centaur vehicles. The baseline mission selections are given in Table 3. The ballistic flight mode requires a high-energy upper stage ($I_{sp} \approx 400$ sec) and has a marginal payload capability even with the 7-segment Titan needed for the Encke and d'Arrest missions. In comparison, solar electric propulsion has far greater performance potential in terms of significantly shorter flight times and greater payload margins.

TABLE 2

COMET RENDEZVOUS SPACECRAFT MODELS

SPACECRAFT SUBSYSTEM	BALLISTIC SPACECRAFT	SOLAR ELECTRIC SPACECRAFT
SCIENCE INSTRUMENTS	70 kg	70 kg
SCAN PLATFORM	15	15
COMMUNICATIONS	28	28
ANTENNA	12	12
DATA STORAGE	14	14
COMPUTER/SEQUENCER	15	20
ATTITUDE CONTROL	45	55
POWER SUPPLY	15	-
BATTERY	10	10
POWER CONDITIONING	11	11
CABLING	20	20
THERMAL CONTROL	12	12
METEOROID PROTECTION	10	10
STRUCTURE	88	88
SUBTOTAL	365 kg	365 kg
10% CONTINGENCY	40	40
PROPULSION	35	5
PROBE	60	60
TOTAL	500 kg	470 kg

TABLE 3

BASELINE MISSION SELECTIONS

COMET/YEAR	MISSION MODE	LAUNCH DATE	FLIGHT TIME (YRS)	ARRIVAL DAYS BEFORE T_P	THRUST TIME (HRS)	LAUNCH VEHICLE	RENDEZVOUS PAYLOAD (KG)	
							NOMINAL	MAXIMUM
ENCKE/80	SEP	3/ 2/78	2.63	50	13,500	T3D/CENT	500	1100
	BALLISTIC	2/23/77	3.51	100	-	T3D(7)/CENT	500	500
d'ARREST/82	SEP	8/13/80	2.03	25	13,700	T3D/CENT	500	690
	BALLISTIC	8/14/77	4.96	50	-	T3D(7)/CENT	500	520
KOPFF/83	SEP	7/14/81	2.03	25	11,600	T3D/CENT	500	630
	BALLISTIC	7/17/79	3.95	50	-	T3D/CENT	500	500
ENCKE/84	SEP	2/26/82	1.97	40	15,000	T3D/CENT	500	560
	BALLISTIC	3/ 4/80	3.93	50	-	T3D(7)/CENT	500	500
HALLEY/86	NEP	5/16/83	2.60	50	14,800	T3D(7)/CENT	500	930
	SEP/GA	8/25/77	8.32	50	27,000	T3D(7)/CENT	500	500

SEP — P_0 = 15 KW, I_{SP} = 3000 SEC

NEP — P_E = 100 KW, I_{SP} = 6000 SEC

BALLISTIC — SPACE-STORABLE RETRO I_{SP} = 400 SEC

GA — JUPITER GRAVITY-ASSIST

Using the programmed Titan 3D/Centaur and a 15 kw SEP powerplant, the flight time to d'Arrest and Kopff is only 2 years. Flight time to Encke is 2.6 years for the 1980 apparition, but can be reduced to 2 years if the mission is delayed to the 1984 apparition.

There are important tradeoffs in the selection of a baseline SEP mission. Parameters of interest are arrival time relative to perihelion, flight time, powerplant size, and propulsion on-time. In general, payload gains are obtained by optimizing any of these parameters. Alternatively, when more than adequate payload is available, certain parameters may be selected "suboptimally" in order to enhance engineering design goals and mission reliability. A SEP power level of 15 kw and a maximum of 15,000 hours of thrust time are such choices. This is thought to be the proper design procedure, even in preliminary mission analyses.

Practical accomplishment of the very difficult Halley rendezvous depends upon the development and availability of nuclear-electric propulsion by 1983. A 100 kw NEP system launched by the Titan 3D(7)/Centaur can delivery more than adequate payload in a flight time of only 2.6 years. Propulsion time is held to 15,000 hours for the nominal 500 kg payload. Use of the proposed Shuttle/Centaur/NEP would allow even further reduction in propulsion time.

Velocity errors at Earth departure and thrust execution errors enroute will cause very large ($1-2 \times 10^6$ km) terminal deviations if left uncorrected. However, the effect of these errors can be measured by the DSN, and trajectory corrections can be made at moderate propellant cost - even in the case of ballistic flights. The ballistic mission to P/Encke requires a total guidance ΔV of about 100 m/sec using three or four impulsive maneuvers. In the case of the SEP mission, it was shown that coast periods during the heliocentric transfer are

important in that they allow the DSN to recover high accuracy tracking of spacecraft position and velocity. The propellant chargeable to all SEP guidance maneuvers is less than 10 kg.

The major error source at rendezvous is the comet's ephemeris uncertainty. Even after comet recovery by Earth-based telescopes the comet's position may be uncertain by many thousands of kilometers. Reduction of this error to the order of 10-100 km can be accomplished only by on-board tracking and trajectory corrections during the approach phase (about 50 days before rendezvous). A non-zero value for the miss distance (about 1000 km is adequate) is required to reduce the range uncertainty. The necessary information can be obtained by a vidicon system which transmits pictures of the comet against a stellar background. However, a study should be made of other on-board tracking systems, such as a scanning photometer, which are less complex and less expensive.

The recommended stationkeeping program requires a ΔV of between 69 (P/Halley) and 167 m/sec (P/Encke). The maneuvers can be performed with the SEP system using less than 6 kg of propellant and less than a 4 percent duty cycle (2.4 days of thrust over a 60-day period).

Many of the details of SEP comet rendezvous missions are illustrated in the study for the 1980 apparition of P/Encke. This mission was selected because P/Encke is scientifically more interesting than the other short-period comets and because two apparitions are available (1980 and 1984). This mission is somewhat demanding and not all conclusions about it apply to the P/d'Arrest and P/Kopff missions. The mission is launched in March 1978, although a 60-day launch window is available at a cost of 15 kg of propellant. Six ion thrusters, each having a 2:1 throttling capability and rated at about 2.8 kw, are used to match the power profile. Maximum operating time of any single

thruster is less than 6000 hours and between one and five thrusters are in a standby mode during the propulsion phase. There is a wide variation of optimum thrust direction relative to the sunline which can be accommodated using rotatable solar arrays. Near the perihelion at 0.34 AU it will be necessary to rotate the arrays to keep their temperature at acceptable levels. Because the comet is approached along the sunline the illumination of the nucleus is good and on-board recovery occurs 60 days before rendezvous at a range of 4×10^6 km. Rendezvous occurs on 17 October 1980 (50 days before perihelion) when P/Encke is 0.26 AU from the earth. During the next ten days when the nucleus is investigated and the probe deployed the data rate is about 3.5×10^8 bits per day. The spacecraft should be equipped with a high gain antenna with two degrees of freedom to handle the large variations in the clock and cone angles of the earth. Data and commands can be exchanged between the spacecraft and the DSN network for at least 20 hours per day during all mission phases.

Further study of rendezvous missions to the periodic comets, with emphasis on a solar electric mission to P/Encke at either the 1980 or 1984 apparition, is warranted. Areas requiring more detailed analysis include: 1) a model for the comet environment, 2) a design for a nucleus probe, 3) the performance penalty for constrained (non-optimum) thrust vector steering and 4) an engineering design for the spacecraft which considers thermal control and the pointing requirements for the science instruments, the antenna and the thrust vector. Technology advances are needed to develop the remote control techniques to be used during the stationkeeping program, the approach guidance TV (or alternate system) and new science instruments for composition determinations of solid particles and energetic ions.

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Technical Memorandum No. M-30
"A SURVEY OF INTERSTELLAR MISSIONS"
By R. K. Brandenburg
July, 1971 (64 pp, 100 refs.)

This short study and literature survey attempts to unify and summarize much of the work done in connection with interstellar missions within the past several years. The report's chief concern is with initial unmanned interstellar probes. Target stellar systems have been accordingly chosen and propulsion systems evaluated with this in mind.

It appears that the first interstellar exploration should be limited to a 20 light-year sphere about the sun. This is due to both our limited knowledge of interstellar space and stellar systems, which decreases with distance, and to the particular short life span and impatience of our species. The 33,500 cubic light-year volume of space contains 59 stellar systems (listed in Table 4), many of which are quite different from our own solar system, but some of which are remarkably similar. Two lists of stellar systems have been compiled, from which the first stellar targets should probably be chosen. The first group was selected in an attempt to maximize the probability of finding life. Admittedly the criteria for selection (similarity to the sun, orbit stability within an adequate temperature zone, and existence of dark companions) are not rigorous, but hopefully future efforts in understanding the origins of life and advances in observational astronomy will enable us to choose targets based on much more stringent qualifications. The second target group was chosen on the basis of astrophysical interest. It includes the nearest members of a wide variety of spectral types and multiple systems.

TABLE 4.

STELLAR SYSTEMS WITHIN 20 LIGHT-YEARS OF THE SUN

STELLAR SYSTEM	DISTANCE (light-years)	RIGHT ASCENSION	DECLINATION	SPECTRAL TYPE	MASS ($M_\odot$)	RADIUS ($R_\odot$)	LUMINOSITY (SUN = 1)
α Centauri	4.3	$14^h36^m.2$	-60°38'	G0(K5,M5)	1.09(0.88,0.1)	1.23(0.87,-)	1.0(0.28,0.000052)
Barnard's Star	6.0	$17^h55^m.4$	+ 4°33'	M5	0.15	~0.12	0.00040
Wolf 359	7.7	$10^h54^m.2$	+ 7°20'	M6	~0.20	~0.03	0.000017
Luyten 726-8	7.9	$1^h36^m.4$	-18°13'	M6 (M6)	—	~0.05(~0.04)	0.00004(0.00003)
Lalande 21185	8.2	$11^h0^m.6$	+36°18'	M2	0.35	~0.35	0.00487
Sirius	8.7	$6^h42^m.9$	-16°39'	A0(wd)	2.31(0.98)	1.8(0.022)	23.0(0.008)
Ross 154	9.3	$18^h46^m.7$	-23°53'	M5	~0.31	~0.12	0.00036
Ross 248	10.3	$23^h39^m.4$	+43°55'	M6	~0.25	~0.07	0.00010
ε Eridani	10.8	$3^h30^m.6$	- 9°38'	K2	0.80	0.90	0.25
Ross 128	10.9	$11^h45^m.1$	+ 1° 7'	M5	~0.31	~0.10	0.00030
61 Cygni	11.1	$21^h4^m.7$	+38°30'	K6 (M0)	0.59(0.50)	0.70(0.80)	0.052(0.028)
Luyten 789-6	11.2	$22^h35^m.7$	-15°37'	M6	~0.25	~0.08	0.00012
Procyon	11.3	$7^h36^m.7$	+ 5°21'	F5 (wd)	1.75(0.64)	1.7(0.01)	5.8(0.00044)
ε Indi	11.4	$21^h59^m.6$	-57° 0'	K5	0.71	1.0	0.12
Σ 2398	11.6	$18^h42^m.2$	+59°33'	M4 (M4)	—	~0.28(~0.20)	0.0028(0.0013)
Groombridge 34	11.7	$0^h15^m.5$	+43°44'	M2 (M4)	0.38	~0.38(~0.11)	0.0058(0.00044)
τ Ceti	11.8	$1^h41^m.7$	-16°12'	G4	0.82	~0.67	0.36
Lacaille 9352	11.9	$23^h2^m.6$	-36° 9'	M2	0.47	~0.57	0.013
BD + 5°1668	12.4	$7^h24^m.7$	+ 5°29'	M4	~0.38	~0.16	0.0010
Lacaille 8760	12.8	$21^h14^m.3$	-39° 4'	M1	0.54	~0.82	0.028
Kapteyn's Star	13.0	$5^h9^m.7$	-45° 0'	M0	~0.44	~0.24	0.0025
Kruger 60	13.1	$22^h26^m.3$	+57°27'	M4 (M5e)	0.27(0.16)	0.51 (-)	0.0013(0.00033)
Ross 614	13.1	$6^h26^m.8$	- 2°47'	M5e	0.14	~0.14	0.00052
BD - 12°4523	13.4	$16^h27^m.5$	-12°32'	M5	~0.38	~0.22	0.0013
van Maanen's Star	13.8	$0^h46^m.5$	+ 5°10'	wdF	-	-	0.00016
Wolf 424	14.6	$12^h30^m.9$	+ 9°18'	M6 (M6)	-	~0.09(~0.09)	0.00014(0.00014)
Groombridge 1618	14.7	$10^h8^m.3$	+49°42'	K5	0.56	~0.5	0.030
CD - 37°15492	14.9	$0^h2^m.5$	-37°36'	M3	0.39	~0.4	0.0058
CD - 46°11540	15.3	$17^h24^m.9$	-46°51'	M4	~0.44	~0.25	0.0023
BD + 20°2465	15.4	$10^h16^m.9$	+20° 7'	M4	~0.44	~0.28	0.0028
CD - 44°11909	15.6	$17^h33^m.5$	-44°16'	M5	~0.34	~0.15	0.00058
CD - 49°13515	15.6	$21^h30^m.2$	-49°13'	M3	0.37	~0.36	0.0044
AOe 17415-6	15.8	$17^h36^m.7$	+68°23'	M3	0.35	~0.39	0.0040
Ross 780	15.8	$22^h50^m.5$	-14°31'	M5	~0.39	~0.23	0.0014
Lalande 25372	15.9	$13^h43^m.2$	+15°10'	M2	-	~0.40	0.0063
CC 658	16.0	$11^h42^m.7$	-64°33'	wd	-	-	0.0008
o Eridani	16.3	$4^h13^m.0$	- 7°44'	K0 (wdA,M5)	0.11(0.44,0.21)	0.7(0.018,0.43)	0.30(0.0040,0.0008)
70 Ophiuchi	16.4	$18^h2^m.9$	+ 2°31'	K1 (K5)	0.89(0.68)	~1.03(~0.84)	0.40(0.083)
Altair	16.5	$19^h48^m.3$	+ 8°44'	A5	590.0	1.2	8.3
BD + 43°4305	16.5	$22^h44^m.7$	+44° 5'	M5	0.26	~0.24	0.0016
AC 79°3888	16.6	$11^h44^m.3$	+78°57'	M4	~0.35	~0.15	0.0008
+15°2620	16.9	$13^h41^m.0$	+15°26'	M1	0.42	~0.50	~0.01
η Cassiopeiae	18.0	$0^h43^m.0$	+57°17'	F9 (K6)	0.85(0.52)	0.84(0.07)	1.0(~0.03)
σ Draconis	18.2	$19^h33^m.0$	+69°29'	G9	0.82	~0.28	~0.4
36 Ophiuchi	18.2	$17^h9^m.0$	-26°27'	K2 (K1, K6)	0.77(0.76,0.63)	~0.90(~0.82,~0.90)	~0.26(~0.26,0.09)
HR 7703	18.6	$20^h5^m.0$	-36°21'	K2 (M5)	0.76(~0.35)	~0.80(~0.14)	~0.20(~0.0008)
HR 5568	18.7	$14^h51^m.6$	-20°58'	K4 (M0)	0.70(0.50)	~0.87(~0.61)	~0.14(~0.017)
Lalande 21258	19.2	$11^h0^m.5$	+44° 2'	M0 (M7)	0.43	~0.47(~0.05)	~0.01(~0.00004)
-21°1377	19.2	$6^h6^m.0$	-21°49'	M0	0.455	~0.59	~0.016
Luyten 97-12	19.2	$7^h53^m.0$	-67°30'	wd	-	-	~0.00003
δ Pavonis	19.2	$19^h59^m.0$	-66°26'	G7	0.98	~1.07	~1.0
Luyten 347-14	19.3	$19^h13^m.0$	-45°42'	M7	0.26	~0.08	~0.0001
+4°4048	19.4	$19^h12^m.0$	+ 5° 2'	M3 (M5)	0.39	~0.43(~0.008)	~0.007(~0.000002)
I (UC 48)	19.5	$17^h38^m.0$	-57°14'	M	0.14	-	~0.0002
-40°9712	19.5	$15^h26^m.0$	-40°54'	M4	0.44	~0.29	~0.003
Ross 47	19.9	$5^h36^m.0$	+12°29'	M5	0.35	~0.17	~0.0008
Luyten 745-46	19.9	$7^h36^m.0$	-17°10'	wdF (M)	-	-	~0.0002(~0.000003)
HD 36395	20.0	$5^h26^m.0$	- 3°42'	M1	0.51	~0.69	~0.02
Wolf 294	20.0	$6^h48^m.0$	+33°24'	M3	0.49	~0.46	~0.008

Perhaps the most scientifically promising stellar systems are those which are common to both groups:

α Centauri
Barnard's Star
ϵ Eridani
Procyon
τ Ceti
η Cassiopeiae

Propulsion systems usable for interstellar flight must be able to provide very high velocities so that the enormous distances[1] involved may be covered in reasonable lengths of time. The propulsion systems examined were chosen to represent a range in "degree of technological advancement". At the near-end of this spectrum is the Nuclear Electric system which is completely inadequate for interstellar flight, even with a growth factor of 100. At the far-end is the photon rocket about which so little is known today that its applicability cannot be adequately assessed. A summary of the findings on propulsion systems is given in Table 5. It would appear from this survey that the Nuclear Pulse and the advanced Fission or Fusion Staged Rocket propulsion systems have the greatest potential for interstellar flight. It is beyond the scope of this report, however, to venture an estimate of the development time necessary for either system.

In summary, interstellar flight and navigation to a variety of "nearby" stellar systems is physically <u>possible</u> within an acceptable length of time. However, within the limits of current and projected technology, it is far from <u>practical</u>.

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1. The nearest stellar system, α Cen, is $\sim 4 \times 10^{13}$ km distant.

TABLE 5

SUMMARY OF POSSIBLE INTERSTELLAR VEHICLE PROPULSION SYSTEMS

PROPULSION SYSTEM	MAXIMUM VELOCITY	FLIGHT TIMES (α CEN. - η CASS.)	REMARKS
Nuclear Electric	$\sim 1.4\times10^{-4}$c (at 3.5×10^{-5}g)	>30,000-128,000 yr.	Representative of current systems-clearly inadequate for interstellar flight
Gaseous-Core Nuclear Rocket	$\sim 1.9\times10^{-3}$c	2,250-9,500 yr.	Available in several decades - inadequate
Nuclear Pulse	$\sim$0.033 c ($\sim$1g for 10^{d})	130-550 yr.	System has potential with development-but is outlawed by international treaty
Advanced Fission and Fusion Staged Rockets	0.3 c (Fission) to 0.6 c (Fusion) ($\sim$1g with mass ratios of 10^4 - 10^7)	16-62 yr. 8-31 yr.	Energy capability is adequate but no practical propulsion systems known
Bussard Interstellar Ramjet	$\sim$0.9 c	$\sim$7-22 yr.	May not be a feasible system due to very low ship densities and nuclear reaction restrictions
Photon Rocket (Matter/Anti-Matter anihilation)	?	?	May represent upper limit of human technology

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Technical Memorandum No. M-31

"A SURVEY OF CANDIDATE MISSIONS TO EXPLORE SATURN'S RINGS"

By W. C. Wells and M. J. Price

October, 1971

The ring system around Saturn is one of the most striking features in the solar system. Exploration of the rings is required for an understanding of their origin and the hazard they represent to spacecraft near Saturn. In addition the rings may provide useful clues to the origin of the solar system. This study examines the problem of ring system exploration and recommends a sequence of missions which will collect the data required.

Earth-based observations have demonstrated that the rings are confined to the equatorial plane and are not more than several kilometers thick. The rings are translucent. The sizes of the ring particles are unknown. Earth-based observations cannot provide the data required to devise a ring system model that can form the basis of studies of the origin and evolution of the rings.

A payload analysis demonstrated that for first generation spacecraft the highest priority instruments are a photopolarimeter, an infrared radiometer and dual band radio occultation. These can be used on any flyby or orbiter spacecraft. Secondary instrument choices for a three-axis stabilized spacecraft such as TOPS are visual imagery and infrared spcectroscopy. Knowledge of the size distribution and surface density of ring system particles will be improved by the data from these remote sensing instruments. A full 180° range in phase angle coverage is desired. Either deployed probes or orbiters (if the risk is acceptable) can also carry meteoroid detectors to directly measure the particle mass distribution and the composition of the rings. Some ring system

properties such as the shape and structure of individual particles and the variation in orbital parameters must be evaluated by a spacecraft in an equatorial, circular orbit. This second generation spacecraft should use the techniques of visual imagery and in-situ sample analysis.

For the five mission concepts which were identified, Table 6 gives the exploration potential of each concept and the desired instruments. The 1977 JSP and 1978 JSUN constrained flyby opportunities do not have a full 180° of phase angle coverage since neither has a solar (or earth) occultation of the spacecraft by the rings (180° phase angle). For the JSP mission there is no 0° phase angle coverage either. From these constrained missions probe deployment is difficult. For an unconstrained mission three types (A, B and C) of targeting were found, all of which have occultations at all ring radii between 1.20 and 2.27 R_S. The type A trajectory stays near the ecliptic plane and also has 0° phase angle coverage over this radial range; however, it can be used only if the saturnicentric declination of the Sun exceeds the declination of the approach asymptote. Probe deployment is also best done from a Type A trajectory and requires a ΔV of less than 50 m/sec.

A Type B trajectory has a 1.25 R_S periapse. However with a 90° argument of periapse, the ring plane is intersected at a distance of more than 2.5 R_S. This targeting results in a near minimum inclination. This trajectory allows examination of the rings at closer range, typically 0.1 R_S, but generally does not have both 0 and 180° phase angle coverage. The latter is also obtained if the solar declination is greater than that of the approach. When arrival conditions do not give occultations with either the Type A or B trajectories, the Type C may be used for this purpose. The spacecraft path is to a point in the ring plane just outside the rings and about 135° from the subsolar longitude. A high inclination (30-45°), which is always available, is chosen.

TABLE 6 CANDIDATE SATURN RING MISSIONS

MISSION CONCEPT	EXPLORATION POTENTIAL	S/C TYPE	USEFUL INSTRUMENTATION	WEIGHT
1. Constrained Flyby	Limited Remote Sensing	TOPS	Photopolarimeter, IR Radiometer, TV	25 kg.
2. Unconstrained Flyby	Good Remote Sensing	Pioneer	Photopolarimeter, IR Radiometer, Radio Occultation	8
3. Elliptical Orbiter	Good In-situ and Remote Sensing	Pioneer	Photopolarimeter, IR Radiometer, Radio Occultation, Impact Mass Spectrometer	13
4. Circular Orbiter	Excellent In-situ and Remote Sensing	New	TV, Radar/Laser, Sample Analysis	90+
5. Deployed Probe	Engineering Data	TOPS Pioneer	Meteoroid Detector, Radio Occultation	2

For an elliptical orbiter a Type A approach trajectory can be used to put the spacecraft into an orbit with a periapse of 2.50 R_s. Again, excellent phase angle coverage is obtained. If ring intersections are desired the periapse radius can be decreased in small steps to 1.25 R_s for 300 m/sec of apoapse velocity changes on a 30-day orbit. A Type B orbit is rapidly perturbed by the oblateness of Saturn resulting in a decreasing radius of ring intersection. For a 30-day orbit, after one year the ring impacts occur at 1.50 R_s. The perturbations can be temporarily offset by small, but critical apoapse impulses. Phase angle coverage is not complete for this orbit but such is the price of a smaller retro propulsion requirement.

The second-generation circular orbiter mission should have the capability of examining the rings at close distance over their full radial extent. This is possible when a nuclear electric propulsion (NEP) system is used for this mission. While performing a spiral orbit capture, the NEP can also be used to maintain a distance of about 10 km above (or below) the ring plane when operation in that plane is hazardous. The instrumentation for this mission will depend on the knowledge gained in earlier ring exploration.

Three launch opportunities were studied for the unconstrained flybys and elliptical orbiters. Launch vehicle and retro propulsion system requirements are given for delivering a 600 lb. Pioneer spacecraft in 1976, 1980 and 1985. The 1976 and 1980 opportunities come before and after the Grand Tour launches and for a launch between these years the illumination of the rings when the spacecraft arrives will be poor. 1985 is the most favorable launch opportunity in its decade. Flybys can be done with a Titan IIID/Centaur/Burner II with a 1000-day flight time. The earth-storable retro propulsion system (I_{sp} = 285) is preferred for Pioneer orbiters and can be used

if the Titan IIID(7)/Centaur/Burner II is available for the launch. A TOPS spacecraft weighing 1400 lbs is generally beyond the capability of the Titan vehicles, although a flyby or a Type B orbiter could be done in 1985.

For the NEP circular orbiter, the availability of the Space Shuttle was assumed. The payload was estimated to be 2200 lbs. plus 440 lbs. for propellant reserve. This mission needs a power of 100 kw and takes a total of 2000 days. The NEP is launched to earth escape and uses a spiral capture to 1.25 R_s at Saturn.

It is recommended that the Saturn ring exploration begun during Grand Tour be continued with a 1980 launch of a Pioneer spacecraft with a probe. This can be followed by a Pioneer orbiter in the mid-1980's. Eventually the NEP circular orbiter will be needed to complete the exploration program. Because these ring missions use only a fraction of the science payload available, the addition of fields and particles and/or planetology instruments should be studied. An engineering and systems analysis of ring penetration probes is also desired to better define this concept.

TABLE 7 SUMMARY OF CANDIDATE MISSION REQUIREMENTS

CANDIDATE MISSIONS	FLIGHT TIME	LAUNCH VEHICLE	CAPTURE I_{sp}	VHP	NET PAYLOAD
1976 Flyby	980^d	5+	-	13.8 kps	620 lbs.
1980 Flyby	1040	5	-	13.6	600
with Probe	1240	5	-	11.8	810
1980 Orbiter (A)*	1490	7	385	8.7	590
(B)	1490	7	285	8.7	600
1985 Orbiter (A)	1500	7	285	8.3	630
(B)	1500	5	285	8.3	640
NEP Orbiter#	2100	#	#	0.0	2640

* Orbit A has 2.50 R_s Periapse, 30d Period
Orbit B has 1.25 R_s Periapse, 30d Period

+ 5 = Titan IIID/Centaur/BII
7 = Titan IIID(7)/Centaur/BII

Shuttle/Centaur, P = 100 kw, I_{sp} = 4500 sec., R_p = 1.25 R_s.

Report No. M-32
"PRELIMINARY ANALYSIS OF VENUS ORBIT RADAR MISSIONS"
by R. K. Brandenburg and D. J. Spadoni
November, 1971 (74 pp, 19 refs.)

This report consists of a short, preliminary analysis of the problems involved in mapping the surface of Venus with radar from an orbiting spacecraft. Two types of radar, the non-coherent sidelooking and the focused synthetic aperture systems, are sized to fulfill two assumed "levels" of Venus exploration. Spacecraft are scaled to accommodate the radars' requirements, and the applicability of ballistic and solar electric delivery modes for the types of missions this analysis suggests is examined.

The two "exploration levels", regional and local, assumed for this study are based on previous Astro Sciences work (Klopp 1969). The regional level is defined as 1 to 3 kilometer spatial and 0.5 to 1 km vertical resolution of 100 percent of the planet's surface. The local level is defined as 100 to 200 meter spatial and 50-100 m vertical resolution of about 10 percent of the surface (based on the regional survey).

Earth-based radar studies of Venus have found that the radar cross section rapidly decreases for wavelengths shorter than 10 cm. The size of the spacecraft's radar antenna is directly proportional to the operating wavelength and thus to keep the antenna's dimensions small it is necessary to choose as short a wavelength as possible. Therefore for this study a 10 cm operating frequency was chosen for both radar systems in order to minimize the antenna size and maximize the apparent radar cross section of the surface.

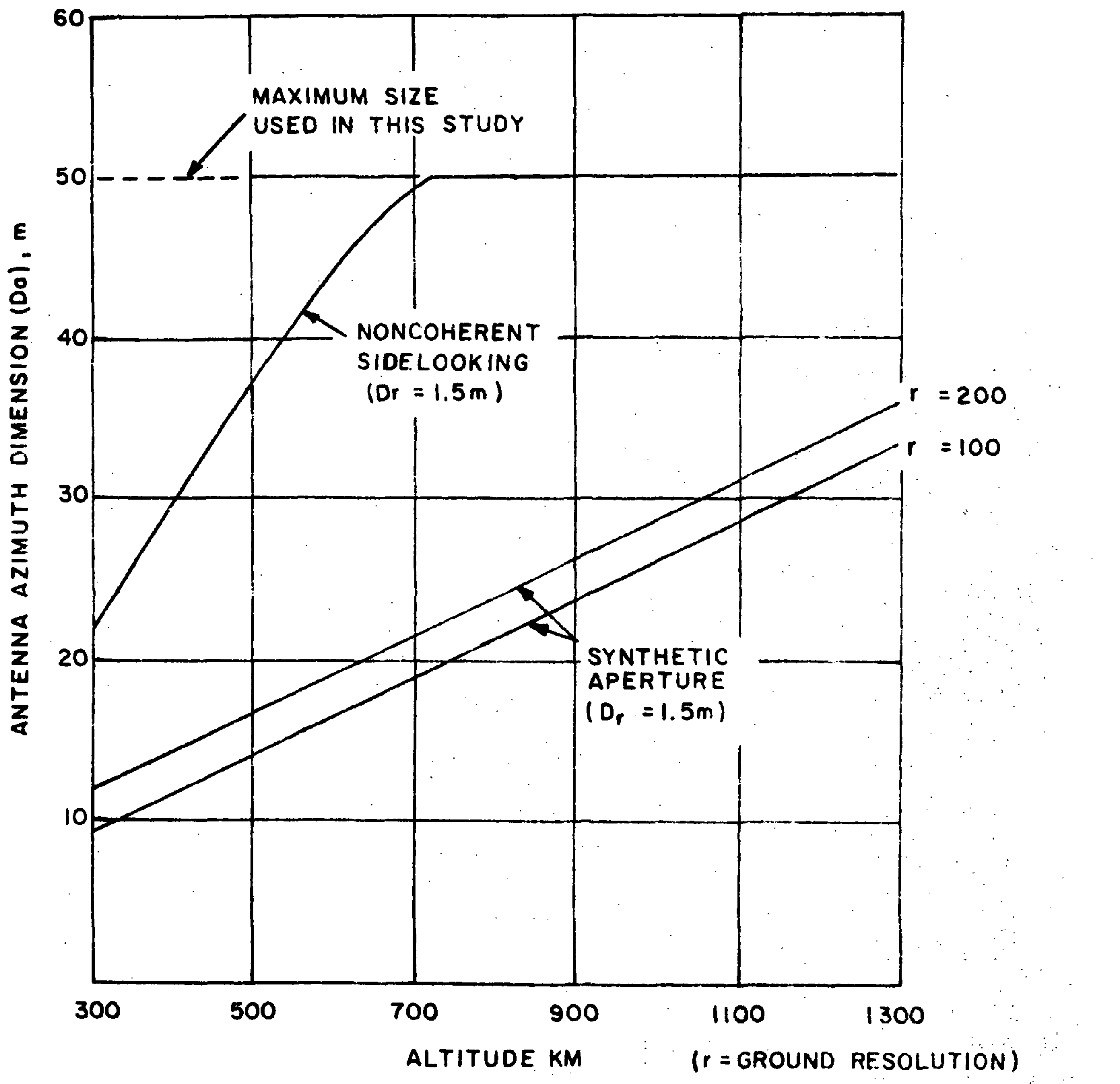
Based on a simplified weight analysis noncoherent radar appears to be the best choice for regional coverage and synthetic aperture for local coverage. A more detailed analysis was

performed and each radar system sized to perform at its respective coverage level at altitudes between 300 and 1300 km (polar circular orbits). The antenna sizes for the two radars are shown in Figure 6. The noncoherent system's antenna was sized to provide an azimuthal resolution of 3 km up to an altitude of 700 km where the antenna length was fixed at 50 m. At altitudes above 700 km, the ground resolution degrades, reaching 6 km at 1300 km altitude.

The synthetic aperture antenna was sized to provide ground resolutions of 100 and 200 m. The synthetic aperture antenna length is less constrained by altitude and beamwidth than the non-coherent system, and the length actually decreases with increasingly finer resolution. The decrease in antenna size is balanced by the increase in input power for finer resolution with the synthetic aperture system. Figure 7 illustrates the variation in required input power with altitude for the two radars. The non-coherent system requires relatively low powers, about 100 watts, for kilometer scale resolution, while the synthetic aperture system may require up to 26 kilowatts for high altitudes.

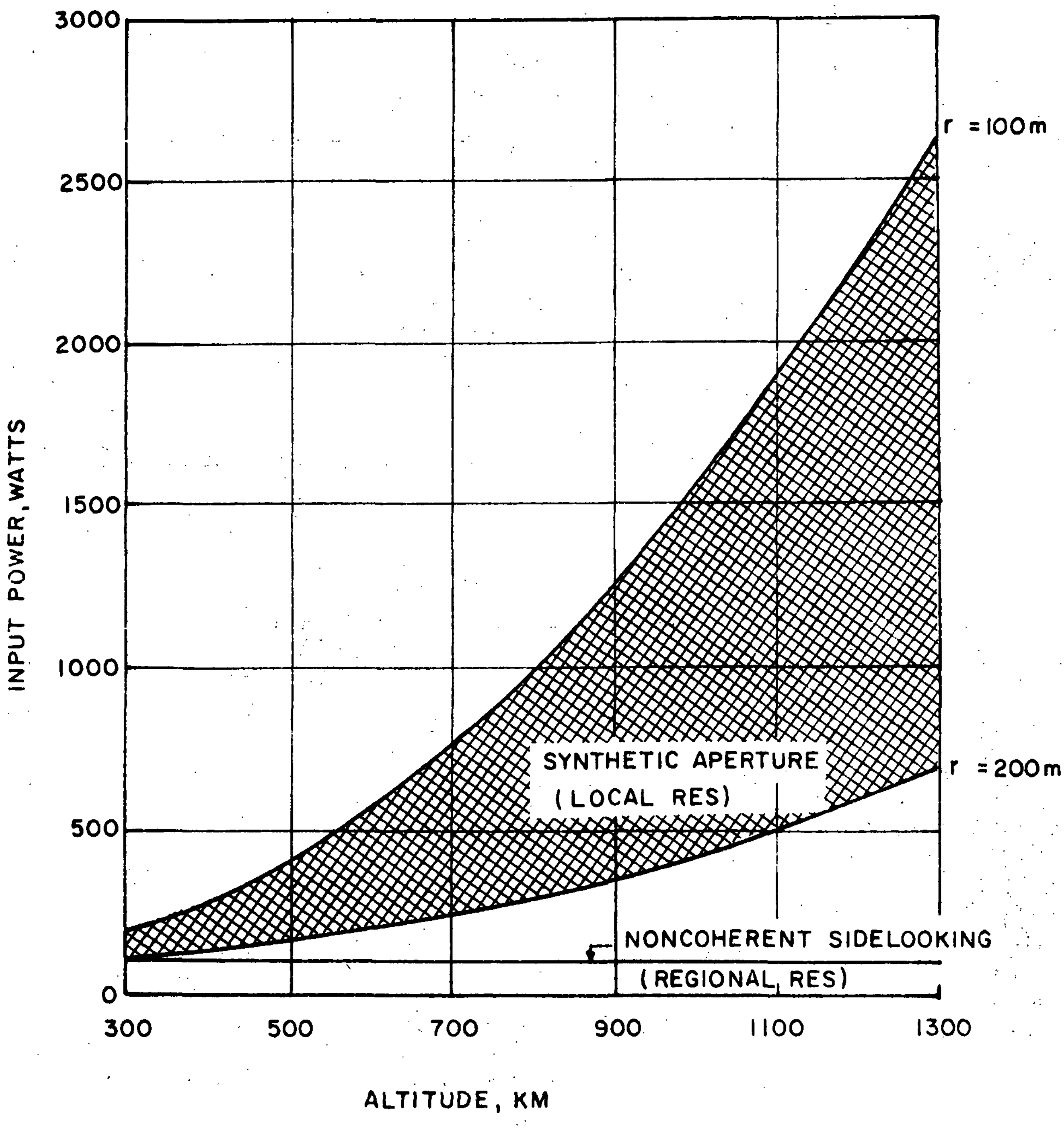
Figure 8 shows the variation in total system weight (antenna plus electronics) for the two types of radar. The non-coherent system is dominated by the antenna weight, as is illustrated by the sharp bend in the curve at the point where the antenna is fixed at 1.5 x 50 m. There are two effects showing up in the synthetic aperture system weights. The 100 m resolution system requires a smaller (and lighter weight) antenna than the 200 m system, but also requires heavier electronics due to higher peak powers. The two effects offset each other to yield a slower weight growth rate with altitude.

Due to the low, circular orbits chosen for this study, the radar mapping spacecraft will be occulted from the sun and



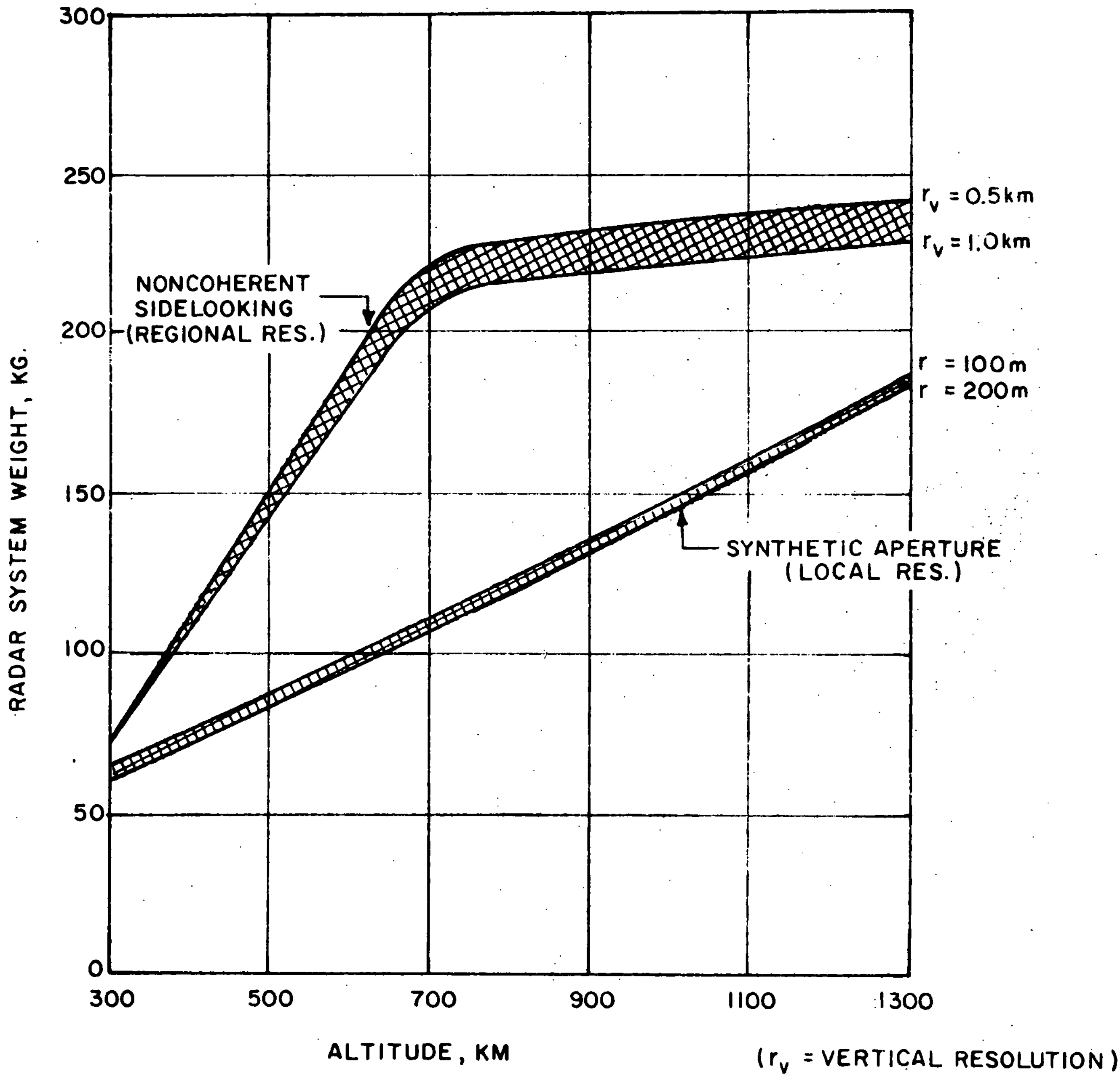
ANTENNA SIZE

FIGURE 6.



INPUT POWER

FIGURE 7.



TOTAL RADAR SYSTEM WEIGHT
(ANTENNA & ELECTRONICS)

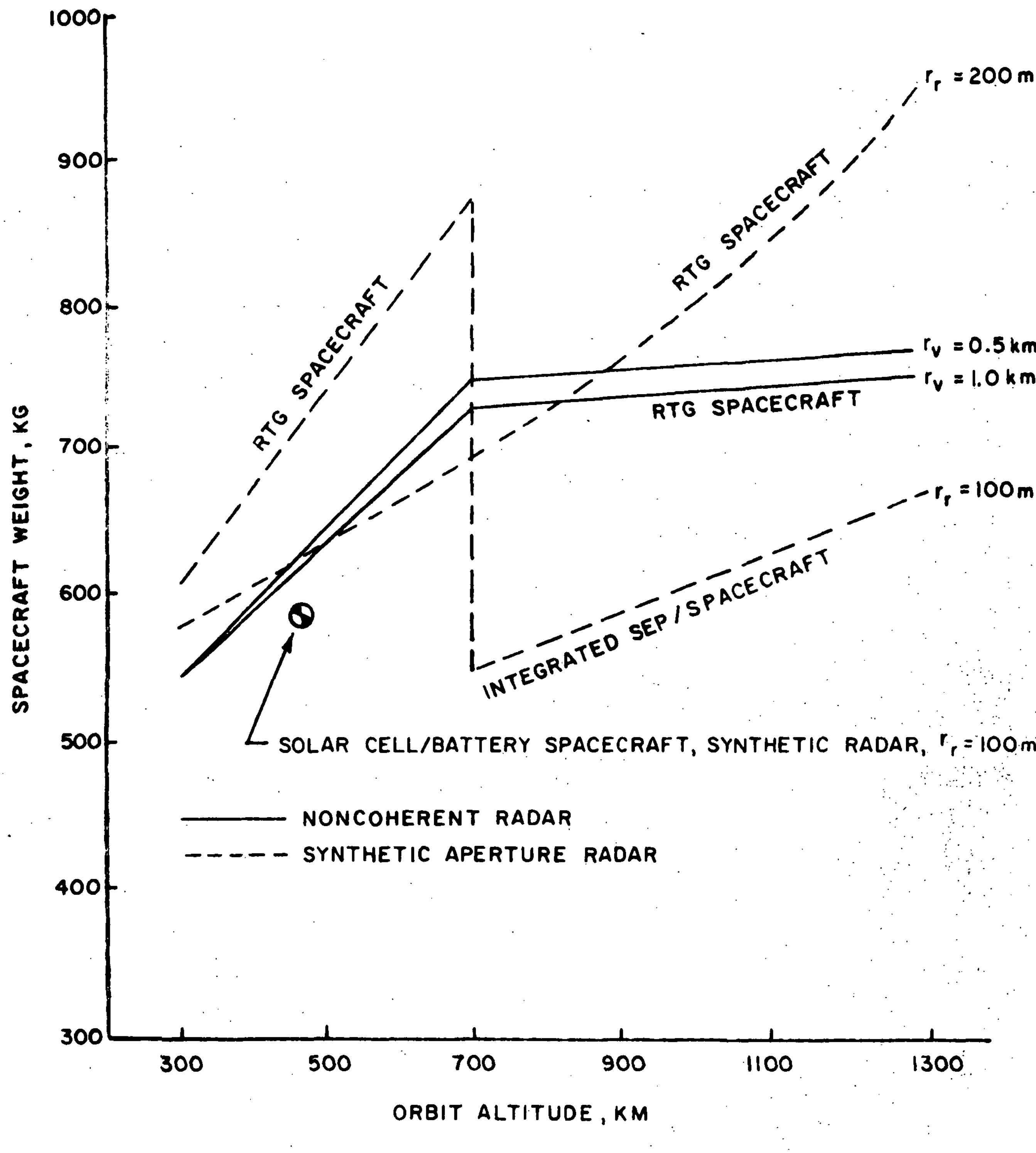
FIGURE 8.

earth for as much as 0.6 hours per orbit. If the spacecraft is powered by solar panels only, it will be able to map 75 percent of the planet's surface during a nominal 120 day mission (worst case conditions). If, however, it uses some sun-independent power system, such as RTG's or solar panels and batteries, it will not be affected by solar occultation and can map 100 percent of the surface in 120 days.

The data telemetry rate is also affected by these occultations. Data is acquired at rates up to 4400 bps for the noncoherent system and up to 2.5×10^6 bps for the synthetic aperture system. However, due to the small swath widths chosen (50-250 km) and the slow sidereal rotation of Venus (1.5°/24 hrs), the spacecraft must wait between 4 and 18 orbits after mapping a swath until the next swath comes into view. Using this time to transmit acquired data, the bit rates can be reduced to about 1000 bps for noncoherent and 2.5×10^5 bps for synthetic aperture.

Figure 9 illustrates the variation in spacecraft weight, sized to accommodate the radar systems. RTG's were used as the power supply up to the point where the radar required more than 750 watts of input power. At this point the solar panels of an SEP stage were used as the power supply (the SEP stage weights are not included on this figure, but are taken into account for the payload analysis). Solar panels were avoided because the spacecraft pointing problems, already significant due to the long range antennas, would only be complicated by their use. The spacecraft communications and data storage systems were based on Mariner '73 and TOPS technology.

The payload capability (net spacecraft weight in orbit) of the Titan IIID/Centaur was analyzed for five launch dates. Of these the 6/5/83 and 12/6/84 launch dates provide enough payload for practically all missions, including the lower altitude ones (which are preferable because of smaller antenna sizes).



VENUS RADAR MAPPING SPACECRAFT, REQUIRED WEIGHT IN ORBIT.

FIGURE 9.

Two dimensional solar electric propulsion data was also analyzed and the Titan IIID/Centaur with a 3.7 kilowatt SEP stage was found to provide ample payload in orbit for all missions.

This study has demonstrated the feasibility of mapping Venus from a radar orbiter. The noncoherent system can provide resolutions of several kilometers but with practical limits on antenna size cannot map at lower resolutions. The focused synthetic aperture radar, however, is not constrained by antenna size and has a very large growth potential. It is clear from this study that 100 percent of the planet's surface can be mapped at 100 m - 200 m using synthetic aperture radar for about the same cost in weight as a 3-km resolution, noncoherent radar.

The trade-offs between solar panels and RTG's still need further study. The RTG system does not have the pointing problems that solar panels do, but this advantage for radar mapping may be outweighed by the thermal problems resulting in the use of multiple RTG power units. Also the communications and data handling systems necessary for synthetic aperture radar require further study. The requirements identified in this study are certainly not impossible but do approach current technological limits.

CONTENTS

SECTION

2.3 COST ANALYSIS

Report No. C-9
"COST MODELING ANALYSIS"
AN INTERIM REPORT
BY P. PEKAR
NOVEMBER, 1971

This study is concerned with the researching and development of cost modeling techniques for application to the production of unmanned planetary spacecraft. Although previous cost modeling efforts have been concentrated on forecasting dollar amounts by major task subdivisions, this study is approaching the problem from a new direction, by using manpower as the forecast unit rather than dollars. Forecasting manpower has in general several distinct advantages over forecasting total cost. Two programs separated in time are only comparable if some inflationary factor is applied to the older program. Such inflationary factors are difficult to formulate and often fail to accurately represent the actual financial conditions within the industry. In addition, the space industry, unlike others, has not as yet been able to use large-scale mass production techniques and thus the total cost of each completed item is not substantially decreased through additional production. The bulk of data collected in the course of this study indicates that the majority of the cost incurred for any program is due to the manpower involved. Although overhead rates may change total costs (eg. University overhead is considerably lower than private industries), manpower varies in proportion to the program's complexity.

Manpower estimates of any new program can be measured against past history to provide an indication of the new estimates' reliability. Once manpower estimates have been established, the conversion of manpower into total cost is

relatively straight-forward. This approach also gives management a tool to evaluate the complexity of a new program in light of previous manpower/complexity relationships.

The difficulties involved in obtaining manpower estimates are formidable. Quarterly reports are submitted to NASA by contractors. These reports are not, unfortunately, a true reflection of total manpower effort. For example, Boeing was the prime contractor for Lunar Orbiter, yet substantial amounts of work were done by RCA and Eastman Kodak, each of which also had subcontractual and inter-divisional work done. When all these are compiled a different picture begins to emerge.

During the past year a mass of cost and manpower data has been acquired for several programs: Mariner 64, 69, and 71, Lunar Orbiter, Pioneer F/G, Surveyor, and Viking Lander. Currently manpower data is being compiled for these programs. (The total direct labor dollars are between 27-30 percent of these programs, and with appropriate overhead rates, direct labor and overhead comprise about 75-80 percent of the total program cost.) Each of these programs will then be categorized into major program elements with associated manpower levels. The final analysis using "Complexity-Labor-Relationships" will express manpower requirements and thus total cost, as a function of program element complexity.

3. SPECIAL STUDIES, ACTIVITIES AND TECHNICAL NOTES

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3.1 Advanced Planning Activities

Within the Long-Range Planning Contract approximately one man year of effort is set aside each year for fast-response technical support to the Planetary Programs Office. In addition to phone calls and real time technical assistance, 17 specific "mini-tasks" were performed in the fast-response mode during the past year as part of this effort. A summary of each task along with relevant figures or tables are included here. These descriptions have been formated to ease identification and organization.

3. SPECIAL STUDIES, ACTIVITIES AND TECHNICAL NOTES

3.1 Advanced Planning Activities

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ADVANCED PLANNING MINI-TASK NO. 1

TITLE: Mission Definition Data

DATE: October 30, 1970

FOR: Mr. Dan Herman, Manager Advanced Programs & Technology

PURPOSE: To define key elements of 1) Encke Rendezvous, 2) MSSR, and 3) Jupiter Entry Probe missions for discussion with OART

RESULTS: Basic mission data including flight profiles, guidance requirements and weight statements were defined. The data were presented in graphs and tables. Each set of mission data was concluded with a list of new technology requirements considered essential to the successful implementation of the mission. These recommendations were essential to Mr. Herman's discussions with OART.

ADVANCED PLANNING MINI-TASK NO. 2

TITLE: Planetary Mission Model Data for VUS Study

DATE: November 12, 1970

FOR: Mr. Nash Williams, JPL

PURPOSE: *To define representative payload/energy requirements* to be used in definition study of Versatile Upper Stage

RESULTS: Performance data were generated for a total of 23 mission examples consisting of 13 different mission definitions. The specific data given for each launch opportunity included characteristic launch velocity, retro impulse at planet, earth escape weight, post-escape propulsion weight, post-escape propulsion Isp, and net useful payload. These data were used by JPL and Battelle Memorial Institute in guiding the Versatile Upper Stage Study performed by General Dynamics, Inc.

ADVANCED PLANNING MINI-TASK NO. 3

TITLE: MSSR Missions Using SEP

DATE: December 1970

FOR: Mr. Ron Toms, Project Engineer (SL)

PURPOSE: To provide SL with SEP data to be factored into their evaluation of MSSR mission requirements.

RESULTS: A short one month study of applying solar electric low thrust propulsion to the 1981 Mars opportunity for sample return missions was performed. It was assumed that SEP would be used on at least one interplanetary transfer leg. Launch vehicles ranging from the Titan III D/Centaur to the Saturn V were considered. Variable power SEP requirements were generated assuming 30 kg/kw, fixed Isp of 3500 sec, and fixed overall efficiency of 66%. Solid (Isp = 300 sec) and space storable (Isp = 400 sec) retro system were considered where necessary. Circular Mars orbits of 1000 km altitude were assumed; return earth-orbits of 555 x 9000 km were used so as to be compatible with Apollo CSM recovery capability. A summary of key results are shown in Table 8. Key parameters in the summary are returned sample size, mission time, launch vehicle, number of launches, and SEP power level.

TABLE 8

MSSR MISSION MODE SELECTION SUMMARY

	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5
TRAJECTORY PROFILE					
MISSION DURATION	950 DAYS	960 DAYS	680 DAYS	600 DAYS	680 DAYS
MARS STAY TIME	41 DAYS	310 DAYS	10 DAYS	20 DAYS	10 DAYS
EARTH-MARS TRANSFER	SEP	BALLISTIC	BALLISTIC	BALLISTIC	BALLISTIC
MARS CAPTURE	SEP	SOLID RETRO	SOLID RETRO	SOLID RETRO	SOLID RETRO
MARS ESCAPE	SEP	SOLID RETRO	SOLID RETRO	SOLID RETRO	SOLID RETRO
MARS-EARTH TRANSFER	SEP	SEP	SEP	SEP/VENUS SWINGBY	SEP
MARS ENTRY	DIRECT	DIRECT	DIRECT	DIRECT	ORBIT
EARTH RECOVERY	ORBIT	ORBIT	ORBIT	ORBIT	ORBIT
DELIVERY SYSTEM					
LAUNCH VEHICLE	TITAN 3F/CENT	TITAN 3D/CENT	INT - 20	INT-20/CENT	SATURN V
NO. OF LAUNCHES	1	2	1	1	1
NO. OF LANDERS	1	1	1	1	2
SAMPLE SIZE	25 LBS	50 LBS	25 LBS	50 LBS	100 LBS
EARTH DEPARTURE WEIGHT	11,500 LBS	9170 / 7350	25,450 LBS	33,500 LBS	71,600 LBS
SEP POWER PLANT SIZE	21 KW	4 KW	29 KW	19 KW	43 KW
SEP PROPULSION TIME	567 DAYS	287 DAYS	245 DAYS	157 DAYS	245 DAYS

ADVANCED PLANNING MINI-TASK NO. 4

TITLE: Literature Survey of Outer Planet Exploration Strategies

DATE: January 18, 1971

FOR: Mr. Ron Toms, Project Engineer (SL)

PURPOSE: To obtain an indication of scientists' interest in outer planet missions

RESULTS: A brief survey of technical journals was performed to assess the degree of consideration given by scientists to outer planet mission strategy. This assessment was to be relatively independent of the formal studies of exploration strategy such as performed by SSB Summer Studies in 1968 and 1970. Six articles were found which dealt with the subject of outer planet exploration strategy. The authors of these articles are S. I. Rasool (Astronautics and Aeronautics, October 1968), J. W. Chamberlain (Astronautics and Aeronautics, January 1970), M. B. McElroy (Journal of the Atmospheric Sciences, September 1969), R. Goody (Journal of the Atmospheric Sciences, September 1969), B. C. Murray (Astronautics and Aeronautics, October 1968), and T. Owen and D. L. Roberts (Bulletin of Atomic Scientists, February 1970). Although this is a small sample, it was apparent that interest in outer planet missions had penetrated the ranks of planetary scientists, with considerable interest in atmospheric missions being expressed.

ADVANCED PLANNING MINI-TASK NO. 5

TITLE: Jupiter Orbit Payload Capability

DATE: January 20, 1971

FOR: Mr. Jay Salmanson and Mr. Ron Toms, Project Engineers (SL)

PURPOSE: To define payload margins for 1977 Jupiter TOPS orbiters.

RESULTS: Orbit Payload capabilities were investigated for the 1977 Jupiter opportunity. Both the five- and seven-segment Titan IIID/Centaur/BII launch vehicles were considered. Retro propulsion systems included earth-storable (Isp = 295 sec), space-storable (400) and solid (315). Trajectory constraints included 15-day launch window, DLA less than 36°, 200 m/sec impulse reserve for guidance, orbit periapse radius of 2 R_J and 15-day orbit period. A fixed 745-day interplanetary trajectory was used with C3 = 92.5 km^2/sec^2 and Vhp = 6.85 km/sec. The propellant reserves for a 1500-lbs TOPS orbit are shown in Table 9 for each launch vehicle/retro combination. Only the seven-segment Titan combined with either solid or space-storable retro propulsion as sufficient capability to perform the mission.

Table 9

PAYLOAD PERFORMANCE MARGINS FOR 1500 LB JUPITER ORBITER*

LAUNCH VEHICLE	EARTH STORABLE	SOLID PLUS VERNIER	SPACE STORABLE
Titan IIID/Centaur/BII	-514 lb	-381	-297
Titan IIID(7)/Centaur/BII	-96	+71	+206

*1977 launch opportunity; $r_p = 2R_J$, period = 15 days

ADVANCED PLANNING MINI-TASK NO. 6

TITLE: Minimum-Period Jupiter Orbits

DATE: January 21, 1971

FOR: Mr. Ron Toms, Project Engineer (SL)

PURPOSE: To determine minimum-period Jupiter orbits for TOPS spacecraft launch between 1976 and 1981.

RESULTS: A brief analysis of orbit period capability was done for Jupiter orbit missions using a 1500 lbs TOPS orbiter. The Titan IIID(7)/Centaur/BII and an earth-storable retro system (Isp = 295 sec) were assumed for propulsion. Constraints used were 20-day launch windows, maximum DLA = 36°, and 200 m/sec impulse reserve for midcourse and orbital maneuvers. Orbit periapse radii of 1, 2 and 3 Jupiter radii were considered. The variation in minimum orbit period was found to be much larger with change of launch opportunity than with different orbit periapses. The 1978 launch opportunity was worst; capture was only possible with $r_p = 1R_J$, the period being 385 days. The 1981-82 opportunity was the best; capture periods of 5.6, 11.5 and 18.6 days were determined for r_p's of 1, 2, and 3 R_J, respectively.

ADVANCED PLANNING MINI-TASK NO. 7

TITLE: Jupiter and Saturn Direct Transfer Data

DATE: March 15, 1971

FOR: Mr. Jay Salmanson, Project Engineer (SL)

PURPOSE: To supply for analysis existing Jupiter and Saturn direct transfer data for 1975-1985.

RESULTS: "Pork-chop" plots were collected for Jupiter and Saturn direct ballistic transfers. The asymptotic approach angle (ZAP) was of particular interest in this task. Data for the 1974 and 1978 launch opportunities to Jupiter and Saturn were taken from a TRW System Group study (Advanced Planetary Probe Study, 1966). Additional launch window constrained data for all Jupiter opportunities from 1974 to 1986, developed in an IITRI study, were enclosed. All other data found in the open literature were either not reduced to graphical form (e.g. NASA's SP-35 Handbook data) or didn't show the desired ZAP angle information in any format.

<u>ADVANCED PLANNING MINI-TASK NO. 8</u>

TITLE: Critique of Saturn-First Outer Planet Grand Tours

DATE: March 19, 1971

FOR: Mr. Ron Toms, Project Engineer (SL)

PURPOSE: To provide an evaluation of the effectiveness of Saturn-first Grand Tour missions.

RESULTS: The following conclusions were drawn from a NASA Center analysis by John W. Young:

1) Saturn-first Grand Tours require higher launch energy than similar Jupiter-first missions, i.e. C3's of 170 versus 130 km^2/sec^2,
2) Total trip time is longer than comparable Jupiter first missions, e.g. E-S-J-P would require 12 years compared to 9 years for E-J-S-P,
3) Retrograde Saturn flybys with r_p lower than the Rings are required,
4) Jupiter flyby conditions with Saturn-first missions are more desirable for science, i.e. close sunny side passes are possible,
5) Launch opportunities occur in the 1980's and 90's, which represent a "second chance" for Grand Tour missions.

An overall preference for the continued planning of Jupiter-first Grand Tour missions in the later 1970's was given.

ADVANCED PLANNING MINI-TASK NO. 9

TITLE: Optimum Periapse Selection for Orbit Capture

DATE: March 19, 1971

FOR: Mr. Ron Toms, Project Engineer (SL)

PURPOSE: To determine the optimum periapse radii for constrained capture orbits.

RESULTS: Five constrained capture conditions were specified for which the optimum capture periapse radius was to be determined. These constraints were:

1) eccentricity = 1 (parabolic orbit)
2) eccentricity fixed between 0 and 1
3) eccentricity = 0 (circular orbit)
4) semi-major axis = constant (fixed period)
5) apoapse = constant

Results of the analysis showed that for constraints 1, 4 and 5, it is always preferable to make the capture radius (orbit periapse) as low as permissible since the optimum r_p is zero. For cases 2 and 3 (3 being a special case of 2) the optimum periapse radius is:

$$r_p \text{ (opt)} = \frac{2\mu}{V_\infty^2} \frac{(1 - e)}{(1 + e)}$$

where μ is the planet gravitational constant, e is eccentricity, and V_∞ is the hyperbolic planet approach speed.

ADVANCED PLANNING MINI-TASK NO. 10

TITLE: Shuttle/Nerva Performance for Outer Planet Missions

DATE: April 5, 1971

FOR: Mr. Dan Herman, Manager - AP&T (SL)

PURPOSE: To evaluate the Shuttle launch requirements of Nerva-based Uranus, Neptune and Pluto missions.

RESULTS: A modular Nerva stage design, combined with the Shuttle, was analyzed with a 1500-lb spacecraft for fast flyby and orbiter missions to Uranus, Neptune and Pluto (flyby only). In all cases at least five Shuttle launches (each launch carrying up to 45,000 lbs of payload) are required to perform the defined missions. For the flybys, trip times to Uranus, Neptune and Pluto are 3 1/3, 5 1/2 and 10 years, respectively. For orbiter missions to Uranus and Neptune (r_p = 2 planet radii, period = 15^d), the respective trip times are about 5 and 8 1/3 years. Cryogenic retro propulsion (Isp = 468 sec) was assumed in the analysis. The Pluto flyby mission time is cut in half (5 years) if 8 Shuttle launches are used, increasing the size of the Nerva stage by three propellant modules. It should be noted that these results are preliminary in that the Nerva performance analysis was simplified to exclude finite thrust losses, and single tank staging was assumed.

ADVANCED PLANNING MINI-TASK NO. 11

TITLE: Comet Missions Material for Dr. Newell's Paper

DATE: May 12, 1971

FOR: Dr. H. Newell

PURPOSE: To prepare data for Dr. Newell for inclusion in paper to be presented at Nobel Institute Symposium.

RESULTS: Dr. Newell planned to present a paper entitled "Comet Missions, Options and Strategy" at the Nobel Institute Symposium "From Plasma to Planets" in September 1971. Five tables and seven figures along with paragraphs of description were submitted for Dr. Newell's consideration. The table and figure titles were as follows:

Table 1. Theories of Comets
" 2. Comet Mission Modes and Characteristics
" 3. Science Questions for Comet Missions
" 4. Comet Mission Science Payloads
" 5. Summary of Fast and Slow Flyby Missions
Figure 1. Candidate Comets for Missions Consideration
" 2. d'Arrest/76 Baseline Flyby Mission Trajectory
" 3. Performance Summary of Comet Rendezvous Missions
" 4. Alternative Mission Trajectories for Halley Rendezvous
" 5. Baseline Mission Trajectories to P/Encke
" 6. Approach Path to P/Encke, 960^d Solar Electric Mission
" 7. Stationkeeping Maneuvers Near P/Encke.

ADVANCED PLANNING MINI-TASK NO. 12

TITLE: Jupiter Orbiter Orbit Selections

DATE: June 16, 1971

FOR: Science Advisory Group, Dr. D. Rea, Chairman

PURPOSE: To select typical orbits for Jupiter Orbiter Missions to be evaluated by SAG.

RESULTS: Mr. Dan Herman requested that orbits selected by JPL and ARC (with IITRI's participation) for analysis of Jupiter orbiter missions be forwarded with the selection rationale to Dr. D. Rea for SAG consideration. This was done by letter, June 16, 1971. The table (10) of orbits selected, including remarks, is included here.

TABLE 10

ORBIT SELECTIONS FOR JUPITER ORBITER STUDIES

NUMBER	INITIAL PERIAPSE (R_J)	FINAL PERIAPSE (R_J)	ORBIT INCLINATION (deg)	GALILEAN SATELLITES ENCOUNTERED	REMARKS
1	1.1	1.01	Minimum *	Io Ganymede	For a comparatively inexpensive but generalized payload to investigate as many objectives as possible.
2A	2.3	2.3	Equatorial +	Io Europa Ganymede	A dual mission set providing sufficient capability to examine nearly all first orbiter objectives. Two spacecraft and probably two launches would be required.
2B	1.1	1.01	30-60	None Planned	
3	4	4	Equatorial +	Io Ganymede	A contingency orbit for a fall-back mission in the event that the Jupiter radiation environment presents insurmountable engineering problems with low periapse orbits.

* Implies an optimum single impulse capture, orbit inclination $\sim$ 5-10°

\+ Implies a three-impulse capture to obtain 0° inclination in Jupiter's planetocentric reference frame

ADVANCED PLANNING MINI-TASK NO. 13

TITLE: Coordination of Cost/Manpower Data for Outer Planet Missions

DATE: July 1, 1971

FOR: Mr. Dan Herman, Manager, AP&T (SL)

PURPOSE: To coordinate the collection of cost/manpower data for NASA/HDQ's Outer Planets Study Plan.

RESULTS: Mr. Dan Herman requested IITRI to structure guidelines and coordinate collection of cost and manpower data for outer planet mission components. These data were used as a basis for generating building blocks for an outer planets program. The building blocks were ultimately included in the presentation of NASA's Outer Planets Program Plans to the 1971 SSB Summer Study, August 1971. The specific project concepts for which data was collected are presented in Table 11 along with the contributors. The specific building block data was forwarded by the contributors directly to NASA/HDQ and was not specifically a part of the coordination effort.

TABLE 11

BUILDING-BLOCK PROJECTS FOR OUTER PLANETS EXPLORATION

ID. No.	PROJECTS TO BE COSTED	CONTRIBUTORS	
		CENTER	CONTACT
1A 1B 1C 1D	PIONEER F/G JUPITER FLYBY PIONEER F/G MODIFIED FOR LONG LIFE (10 YRS) PIONEER F/G MODIFIED TO JUPITER ORBITER PIONEER F/G MODIFIED TO ATM PROBE CARRIER	ARC	B. PADRICK
2A 2B 2C	TOPS GT FLYBY TOPS GT MODIFIED TO JUPITER ORBITER TOPS GT MODIFIED TO ATM PROBE CARRIER	JPL	J. LONG
3	JUPITER TURBOPAUSE PROBE	GSFC	G. LEVIN
4A 4B 4C	OUTER PLANET ENTRY PROBE (10 ATM) OUTER PLANET ENTRY PROBE (100 ATM) OUTER PLANET ENTRY PROBE (300 ATM)	ARC & JPL	B. PADRICK & J. LONG
5A 5B	SOLAR ELECTRIC PROPULSION SUBSYSTEM (10 KW) SOLAR ELECTRIC PROPULSION SUBSYSTEM (15 KW)	OART	J. LAZAR

ADVANCED PLANNING MINI-TASK NO. 14

TITLE: Propulsion Comparisons for Jupiter Orbiter Missions

DATE: July 15, 1971

FOR: Mr. Dan Herman, Manager, AP&T (SL)

PURPOSE: To compare performance of several propulsion system combinations for 1976 and 1978 Jupiter orbiter missions.

RESULTS: Results of Jupiter orbit payload versus flight time were generated for the following propulsion options:

1) Titan 3D/Centaur/Burner II - ES Retro (285)
2) Titan 3D/Centaur/Burner II - SS Retro (385)
3) Titan 3D(7)/Centaur/Burner II - ES Retro (285)
4) Titan 3D/Centaur/SEP (5KW) - ES Retro (285)
5) Titan 3D/Centaur/SEP (15KW) - ES Retro (285)

The Jupiter orbit specified for this analysis was r_p = 4 Jupiter radii, period = 21 days. Both the 1976 and 1978 launch opportunities were considered. For options 1-3 the payloads ranged between 200-300 kg, and 400-600 kg in 1976 and 1978, respectively; optimum flight times were 750^d and 630^d (due to launch constraints), respectively. For options 4 and 5 the payload was essentially independent of launch opportunity. Specific data points given were 450 and 700 kg at 800 days and 550 and 850 kg at 1000 days for options 4 and 5, respectively.

ADVANCED PLANNING MINI-TASK NO. 15

TITLE: Summary of Comet Mission Data

DATE: July 21, 1971

FOR: Mr. Dan Herman, Manager, AP&T (SL)

PURPOSE: To provide a comparative summary of missions to various comets with several mission modes.

RESULTS: This short task was essentially a compilation of existing comet mission data into a single table to compare characteristics for fast flyby (FFB), slow flyby (SFB), and rendezvous (R) mission modes to several comets and opportunities. The data are summarized in Table 12. The science payloads shown are weight estimates for each mission mode, i.e. FFB - 35 kg, SFB - 50 kg, and R-70 kg. The launch vehicles indicated are those required to deliver these science payloads, supporting subsystems (spacecraft), and post-launch propulsion (where necessary) to complete the respective missions.

TABLE 12

COMET MISSIONS SUMMARY

COMET	APPARITION ENCOUNTER MODE	SCIENCE PAYLOAD (KG)	LAUNCH DATE	PROPULSION	ENCOUNTER PARAMETERS: DATE	DAYS FROM R_p	VELOCITY (KPS)	DURATION
d'ARREST	1976/FFB	35	6/3/76	TAT(6C)/DELTA/BII	8/17/76	+4	12.4	0.9^h
ENCKE	1980/SFB	50	3/1/79	TITAN 3C/SEP(10KW)	11/20/80	-10	1.5	7.4^h
d'ARREST	1982/R	70	8/13/80	TITAN 3D/CENT/SEP (15KW)	8/23/82	-25	0	100^d
KOPFF	1983/R	70	7/14/81	TITAN 3D/CENT/SEP (15KW)	7/24/83	-25	0	100^d
ENCKE	1984/R	70	3/18/82	TITAN 3D/CENT/SEP (15KW)	2/16/84	-40	0	100^d
HALLEY	1986/FFB	50	7/4/85	TITAN 3B/CENT/BII	12/11/85	-60	55	0.2^h
		50	9/7/85	TITAN 3B/CENT/BII	3/5/86	+25	75	0.15^h
	1986/SFB	50	9/29/78	TITAN 3D/CENT/SEP(15KW)	9/12/85	-150	6.4	1.7^h
	1986/R	70	5/16/83	TITAN 3D(7)/CENT/NEP (60KW)	12/21/85	-50	0	100^d

ADVANCED PLANNING MINI-TASK NO. 16

TITLE: 1971 PEPP Mission Sheets

DATE: August 18, 1971

FOR: Mr. Paul Tarver, Project Engineer

PURPOSE: To update a number of PEPP Mission Sheets for NASA/HDQ/SL advanced planning purposes.

RESULTS: Seventeen PEPP Mission Sheets were partially updated for Mr. Paul Tarver. The 17 missions for which data was provided included the following:

1) Mars Soft Lander/Rover - 1981 (MSL/R-81)
2) Venus High Data Orbiter - 1981 (VHO-81)
3) Venus Mariner Orbiter/Rough Landers - 1986 (MSL/R-81)
4) Mercury Solar Electric Orbiter - 1982 (MeSO-82)
5) Jupiter Pioneer Orbiter - 1976 (JPO-76)
6) Jupiter Pioneer Tandem Orbiters - 1976 (JPTO-76)
7) Jupiter Pioneer Orbiter - 1978 (JPO-78)
8) Jupiter Mariner Orbiter - 1982 (JMO-82)
9) Jupiter Pioneer Probe - 1980 (JPP-80)
10) Jupiter Ganymede Soft Lander - 1985 (JSSL-85)
11) Saturn Pioneer Orbiter - 1978 (SPO-78)
12) Saturn Pioneer Orbiter - 1980 (SPO-80)
13) Uranus Probe - 1984 (UP-84)
14) Comet d'Arrest Mariner Flyby - 1976 (CMF-76)
15) Comet Halley Mariner Flyby - 1985 (CMF-85)

16) Encke Rendezvous - 1978 (CMR-78)
17) Asteroid Belt Solar Electric Flythru - 1975 (ASF-75)

An example of these sheets is given in Figure 10 for the first mission, MSL/R-81. Note that the items under Mission Requirements have been left blank. The mission sheets were distributed to JPL, MSFC and ARC, as appropriate, for completion of these data. The sheets were then returned directly to Mr. Tarver.

FIGURE 10 PEPP MISSION SHEET EXAMPLE (1971 UPDATE)

- TITLE: Mars Soft Lander/Rover MISSION NO. MSL/R-81
- LAUNCH DATE: 1981 NO. OF LAUNCHES: 1
- WEIGHT (lbs): INJECTED 2750 ORBITED
  ENTERED 2250 LANDED 1500
  SCIENCE 100
  OTHER
- CHARACTERISTIC VELOCITY (fps): 37,650 C3 (km^2/sec^2): 10
- CANDIDATE LAUNCH VEHICLE (lbs injected): Titan IIID (4200)
- MISSION OBJECTIVES: Visual characterization of several different surface areas, search for life in unaltered sites, temporal, spatial and altitude variations of atmosphere, deployment of a seismic network, extend all surface experiments to a broad area (~ 500 km)
- MISSION CHARACTERISTICS: Launch occurs during a 20-day window; 500 lbs are allotted for interplanetary cruise systems; direct entry is assumed at Mars with entered wt. = 1.5 landed wt.; the landed rover has a one-year surface lifetime.
- MISSION REQUIREMENTS:
  MAJOR FACILITIES
  MAJOR NEW TECHNOLOGIES
- REMARKS:

ADVANCED PLANNING MINI-TASK NO. 17

TITLE: Natural Satellite Capture by Jupiter

DATE: August 26, 1971

FOR: Mr. Jesse Moore, Project Engineer, AP&T (SL)

PURPOSE: To draft a response regarding a letter concerning natural satellite capture received by Dr. von Braun's office.

RESULTS: A letter was received from Dr. J. M. Bailey of The George Washington University regarding a theory for the capture of Jupiter's irregular satellites and the possible application of this technique to a 1975 Jupiter flyby mission. Basically, the response indicated that the available free capture orbits were of questionable scientific value, having a minimum period of 250 days and a closest approach to Jupiter of greater than 100 planet radii. Furthermore, to modify these orbits to much more desirable elliptic orbits (e.g. $r_p \times r_a = 1.1 \times 160$) would require almost three times as much impulse as a direct capture into the same orbit. However, a number of suggestions were made regarding other possibly fruitful applications of the technique, e. g. an interplanetary monitoring station, Pluto orbiter, and satellite orbiter of a major planet.

3.2 The Cometary Science Working Group.

The Cometary Science Working Group, organized by IITRI at NASA-OSSA's request met at Yerkes Observatory, Williams Bay, Wisconsin on June 9, 10, and 11, 1971. Dr. C. R. O'Dell, Director of Yerkes, chaired the meeting and Mr. D. L. Roberts, Manager of Astro Sciences, served as meeting secretary and editor of the proceedings. A list of attendees is given at the end of this summary.

SUMMARY

The Cometary Science Working Group considered in detail the objectives of cometary investigations, the need for ground based observations and the types of space missions which would best meet the objectives in the period 1975 to the mid 1980's.

Although much is known and understood about comets it was clear that there are fundamental questions which still need to be answered and that space missions can uniquely contribute to obtaining the answers. The major contributions that space missions can make are, in priority order:

- To identify parent molecules released by the nucleus before they dissociate in the coma.
- To measure the composition of tail constituents and the electromagnetic environment in the tail.
- To define the nature of the cometary nucleus.

In defining ways in which solutions to the major cometary questions can be provided, the need for ground based observations, laboratory research and theoretical studies were emphasized repeatedly. The ultimate scientific return from space missions will depend heavily on the ground based research

into cometary phenomena that precedes the missions.

Experimental payloads were identified for each class of mission (fast and slow flyby and rendezvous). The measuring instruments most highly recommended for all classes were:

Mass Spectrometer

Solid Particle Composition Analyzer

Ion Composition Detector

Plasma Properties Detectors.

Beyond this group, and having a lower priority was an imaging experiment which could serve for comet acquisition, as a visual imager, and as an imaging photometer.

The mission types considered were fast flyby (5-50 km/sec approach velocity), slow flyby (1-5 km/sec approach velocity) and rendezvous (0-100 m/sec). Fast flyby is the simplest and least expensive and can yield a high scientific return if the mission profiles are carefully selected. The mission should be targeted to within 1000 km of the nucleus to measure parent molecules and this generally excludes tail experiments. However multiple fast flyby missions (minimum of two spacecraft) can cover additional interesting regions of the comet and provide a very significant scientific return. Slow flybys and rendezvous provide greater scientific return than fast flyby but they are more complex and more expensive mission modes. <u>For initial cometary missions, fast flyby was strongly endorsed as a good mission mode</u>.

Missions to D'Arrest, Encke and Halley were discussed. The D'Arrest '76 mission was unlikely to materialize unless almost complete spares from Pioneer or Mariner missions can be made available. Encke fast flyby missions could be achieved with planetary explorer or Mariner type spacecraft in 1980 or 1984. For slow flyby or rendezvous with Encke, solar electric propulsion is very desirable. However it was not considered reasonable to use the first flight of a solar electric spacecraft on a comet rendezvous mission.

Missions to Halley's comet in 1986 were highly recommended. The suggestion of multiple flybys using Planetary Explorer or Mariner type spacecraft was very strongly endorsed.

COMETARY SCIENCE WORKING GROUP

LIST OF INVITEES:

COMETARY SCIENCE

C. Arpigny	University of Liege
J. Brandt	NASA/GSFC, Code 614
A. Delsemme	University of Toledo
W. Jackson	NASA/GSFC, Code 692
B. Marsden	Smithsonian
C. O'Dell	Yerkes Observatory
G. Wetherill	University of California
F. Whipple	Smithsonian

EXPERIMENT EMPHASIS

K. Anderson	University of California
H. Bridge	Massachusetts Institute of Technology
A. Code	University of Wisconsin
J. Hayes	Indiana University
A. Nier	University of Minnesota
D. Rea	NASA/JPL
R. Soberman	Drexel University

MISSION ANALYSIS

D. Bartz	NASA/JPL
R. Bourke	NASA/JPL
A. Friedlander	IIT Research Institute
J. Long	NASA/JPL
J. Moore	NASA/JPL
J. Niehoff	IIT Research Institute
D. Roberts	IIT Research Institute

COMETARY SCIENCE WORKING GROUP

NASA HEADQUARTERS

W. Brunk	Code SL
L. Burlaga	Code SL
M. Dubin	Code SG
D. Herman	Code SL
R. Kraemer	Code SL
J. Lazer	Code RNT
M. Mitz	Code SL
J. Mullin	Code RNT
H. Newell	Code AA

OBSERVER

Prof. Israel	ESRO

3.3 Computer Programs Developed

The following computer programs were developed for use on several of the studies performed under Contract NASW-2144 and added to the Astro Sciences program library within the last year.

<u>EPEC</u>: Interplanetary trajectory computer programs generally yield arrival excess velocity vectors in Earth ecliptic coordinates. EPEC will transform the right ascension and declination of the VHP vector from Earth ecliptic to target-planet-centered equatorial coordinates. This program was written for the Hewlett-Packard 9100 system.

<u>APPROACH:</u> Solves the targeting problem for planetary entry probes ejected from fly-by spacecraft. Computes deflection increment, entry conditions and sensitivities, as well as post entry probe to spacecraft range and communication angle.

4. PAPERS PRESENTED AND PUBLISHED

"TRAJECTORY REQUIREMENTS FOR COMET RENDEZVOUS"
By A. L. Friedlander, J. C. Niehoff, and J. I. Waters
in: Journal of Spacecraft and Rockets, Vol. 8, No. 8, Aug. 1971 pp 858-866.

This paper presents a new look at spacecraft mission opportunities to the short-period comets in the time period 1975-1995. The objective is to identify the most promising rendezvous opportunities and flight modes from the standpoint of trajectory requirements and launch vehicle/payload capabilities. A "broad-brush" treatment of wide scope underlies the analysis. Selection criteria leading to 16 comet apparitions for study are described. The candidate flight modes include; 3-impulse ballistic transfers, Jupiter-gravity-assist transfers, solar-electric and nuclear-electric low-thrust transfers. Results show that the best early opportunities are Comets Encke/80, d'Arrest/82, and Kopff/83. Although these missions can be performed ballistically, solar-electric propulsion offers greatly improved performance. Practical accomplishment of the very difficult Halley rendezvous depends upon the development and availability of nuclear-electric propulsion by 1983.

"JUPITER ORBITER MISSIONS"

By J. C. Niehoff and W. C. Wells

Presented at the 17th Annual Meeting of the American Astronautical Society, June 28-30, 1971, Seattle, Washington

Objectives for Jupiter exploration are used to obtain science instruments and preferred orbits for candidate orbiter spacecraft. The two missions studied are: (1) a planetology and satellite emphasis mission using a 14.22 day equatorial orbit and (2) a planetary environment and planetology mission using an inclined 21 day orbit. The launch years considered are 1974-1985. Operations during orbit are discussed, including satellite encounters, event timing and instrument operations.

"AN ASSESSMENT OF COMET AND ASTEROID MISSIONS"
By J. C. Niehoff
Presented at the 17th Annual Meeting of the American Astronautical Society, June 28-30, 1971, Seattle, Washington.

The characteristics and requirements of comet and asteroid missions are reviewed. Considered flight modes include flyby, rendezvous, docking and sample-return. Science and spacecraft payloads are suggested for each of these modes. It is argued that a balanced space program should include comet and asteroid missions. A sequential program of missions, beginning with relatively uncomplicated flybys, appears most reasonable. The single addition of solar-electric propulsion provides the most flexibility and adds a margin-of-growth for follow-on missions.

"SAMPLE RETURN MISSIONS TO THE ASTEROID EROS"

By J. C. Niehoff and A. C. Mascy*

Presented at the Twelfth Colloquium of the International Astronomical Union, "Physical Studies of Minor Planets", University of Arizona, Tucson, Arizona, 10 March, 1971.

Solar-electric low-thrust and multi-impulse ballistic energy requirements are investigated for sample-return missions to the asteroid Eros. Launch opportunities from 1975 to 1984 are identified. A payload analysis is performed which includes science instrument selection, station-keeping definition and assessment of sample collection requirements. It is concluded that for the favorable 1977 opportunity either a Titan IIID/Burner/SEP(10 kw) or Titan IIID(7)/Centaur/Space Storable (385 sec I_{sp}) propulsion system is required to return a 25 kg sample from Eros to a 12-hour earth orbit in a total flight time of three years. Launch range safety and rendezvous communications are identified as problem areas requiring further study.

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* Research Scientist, NASA Advanced Concepts & Mission Division, OART, Moffett Field, California.

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5. BIBLIOGRAPHY OF AS/IITRI REPORTS AND TECHNICAL MEMORANDA

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6. MAJOR COMPUTATIONAL CODES

6. MAJOR COMPUTATIONAL CODES

The following computer codes have been written or adapted for use on contract studies between March 1963 and October 1971.

INTERPLANETARY TRANSFERS

Conic Section Codes

SPARC: The JPL general conic section code for ballistic and ballistic-gravity-assist flights.

ASC CONIC: An extensive collection of programs and subprograms for ballistic and gravity-assist flights and accessible regions calculations, and for conic guidance analysis.

TOPSY: Determines the minimum ideal velocity and the corresponding time required to reach any point in the solar system.

High Precision Codes

NBODY (II): The Fortran II version of the Lewis Research Center code has been used for comet perturbation analysis, considering the gravitational effects of Sun and planets simultaneously.

NBODY (IV): The Fortran IV version of this has been revised at ASC for multibody, high precision targeting and guidance analysis.

Low Thrust Codes

JPL CODE: The JPL Calculus of Variations Optimized Thrusted Trajectory Code has been used for optimum interplanetary nuclear electric flight with variable thrust, constant thrust, or constant acceleration.

UNITED AIRCRAFT CODE: Computes optimum low thrust (nuclear-electric) interplanetary trajectories under constant thrust conditions. Method employed is calculus of variations and finite difference Newton-Raphson Algorithm. Powerplant mass fraction and specific impulse can be optimized if desired.

BOEING CODE: CHEBYTOP is a fast generator of optimum low thrust interplanetary trajectories. Both solar-electric and nuclear electric powerplants can be treated. Propulsion system parameters must be specified - payload optimization can be accomplished by multiple parametric runs.

MULIMP: Uses Conjugate-Gradient search method to find minimum, ΔV trajectories consisting of up to four free fall conic arcs separated by up to five impulses. Departure is from Earth orbit and the arrival point is constrained to lie on an arbitrary conic. Velocity is matched at the arrival point (rendezvous).

Near Planet Operations

ATMENT: One of a series of codes for integrating the atmospheric entry for a spacecraft.

ZAYIN: A Fortran II code (from W. P. Overbeck) modified for calculating satellite orbits around the Earth, including oblateness and air drag.

GNDTRC: Generates lunar ground traces for specified lunar orbits.

LIMITS: Computes maximum velocity and maximum energy change as a function of miss distance from a given gravity-assist body.

KOFNAL: Generates ground traces of orbiting spacecraft for any number of desired revolutions. Can be used for all nine planets of the solar system. Has Calcomp capability for plotting longitude and latitude of the ground trace.

CONTUR: Generates data for Sun, Earth & Canopus occultation contours for hyperbolic flybys past any given planet.

AMSOCC: Generates data for Sun, Earth & Canopus occultation contours for orbiting spacecraft about any given planet.

HYPTRC: Computes 2-D planetary encounter trajectories in polar coordinates given heliocentric transfer trajectory from Earth.

TRACE: Generates Earth ground traces for specified Earth orbits.

PROFYL: A planetary encounter profile definition code.

RINGER: A code of calculating crossings of Saturn's ring plane during flyby.

PETARD: Similar to "KOFNAL". Generates ground traces orbiting spacecraft for any number of desired revolutions for any of the nine planets of the solar system. Has Calcomp capability for plotting latitude or altitude as a function of time from periapse on semi-log plots.

CAPTR: Set of two codes developed to perform orbit and landing maneuvers about a natural planetary satellite.

ETY 1: Solves differential equations describing motion of a spacecraft entering the atmosphere of a rotating planet with a spherical gravity field. Present version assumes fixed values of the drag coefficient and lift to drag ratio. Atmospheric density is computed as an exponential function of altitude.

Guidance and Orbit Determination

ORBDET: Orbit determination for an overdetermined set of points by Kalman filtering.

LTNAV: A low thrust navigation code.

PARODE: A radio tracking performance evaluation code for orbit determination during planetary approach.

COMODE: High precision comet orbit determination code, taking into consideration gravitational effects of Sun and all nine planets simultaneously.

ORBOBS: A Fortran IV program for determining minimum separation intercepts of a Jupiter orbiter with the four Galilean Satellites; Io, Europa, Ganymede, and Callisto.

CELESTIAL TRACKING: A celestial tracking performance evaluation code for orbit determination during planetary approach.

SURVEY: Generates sighting conditions for comets over a specified length of time. Has Calcomp capability for plotting sighting conditions as function of time from perihelion.

Combinatorial Codes

XPSLCT and COMBSC - find various sets of payloads from experiments and instruments, subject to spacecraft constraints.

HFIT: A code for least square fit of a set of points to a hyperbola.

BIMED: A general statistical analysis package from UCLA used for multiple regression analysis.

IMP 3: An integer programming code.

Space Sciences Codes

GPSS-III: An IBM system for analyses of systems of discrete transactions.

MIMIC: A Fortran IV-like system for simulating, on the 7094, an analog computer and thereby easily doing integrations.

KWIC-II: The IBM key work in context system used to catalog the ASC library of some 8000 documents.

ORBITAL ELEMENTS TAPE: An extensive collection of orbital elements for solar system objects, including planets, 1600 numbered asteroids, 2000 unnumbered asteroids and hundreds of comets.